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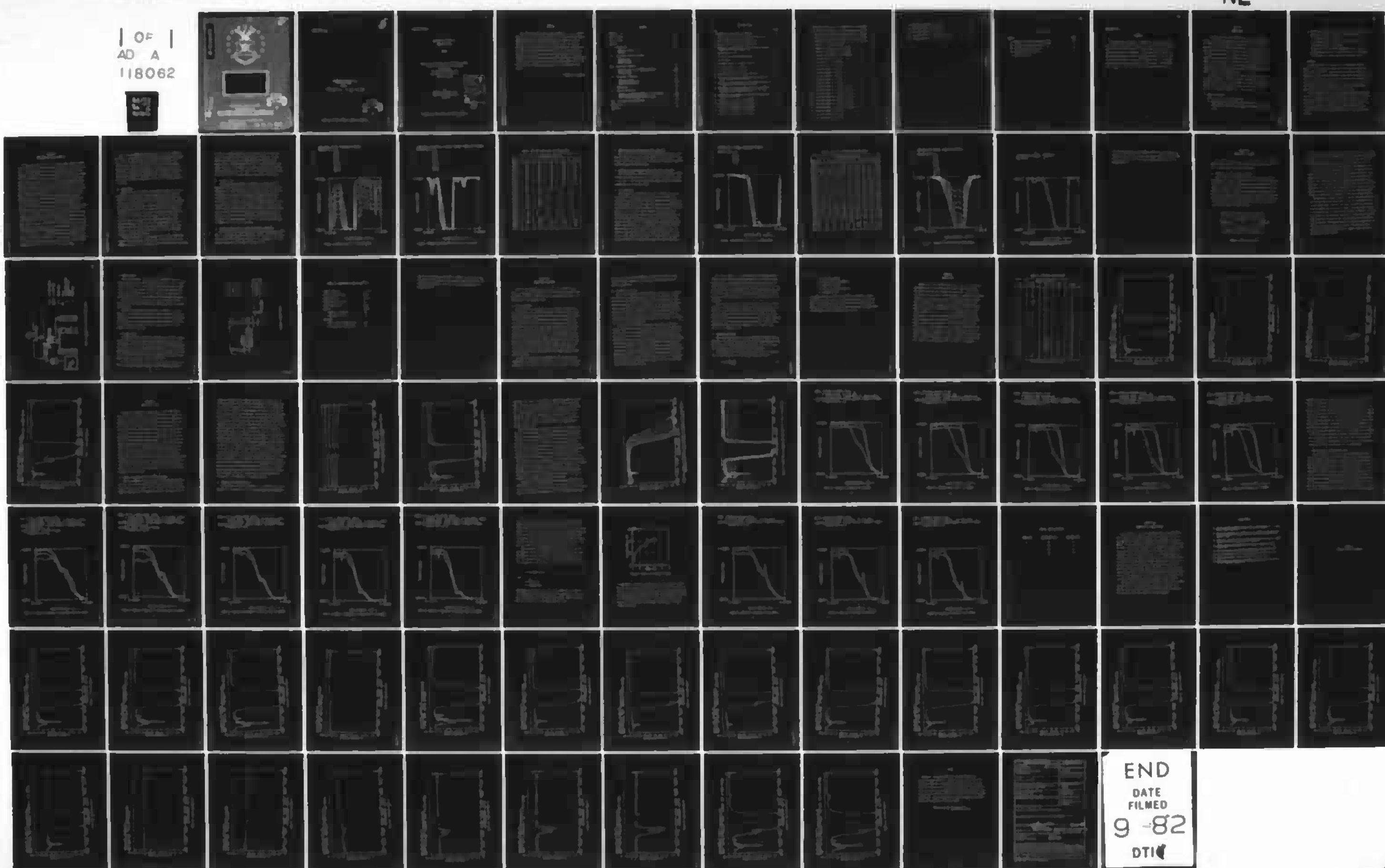

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DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY (ATC)

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GEP/PH/82J-1

ATMOSPHERIC ABSORPTION CELL
CHARACTERIZATION

THESIS

AFIT/GEP/PH/82J-1 Nicholas A. Pequignot

AFIT/GEP/PH/82J-1

ATMOSPHERIC ABSORPTION CELL CHARACTERIZATION

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

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by
Nicholas A. Pequignot, B.S.
Graduate Engineering Physics
June 1982

PREFACE

The study described herein was performed during the period June 1981 to February 1982 in the Avionics Laboratory/Electronic Warfare Division, Infrared Measurements Facility at Wright-Patterson AFB, Ohio, 45433, as a research project for the Air Force Institute of Technology (AFIT). The study was proposed by Dr. Richard Sanderson of the Avionics Laboratory. The support of Mr. Charles Bond of Systems Research Laboratories, Inc., in evaluating the absorption cell vacuum integrity and of Mr. Eugene Salzman of the Avionics Laboratory in making the measurements was greatly appreciated. Acknowledgement is given to Dr. R. Sanderson, Major James Lange, and Dr. Robert Hengehold for their assistance in discussions concerning the technical portions of this effort.

Nicholas A. Pequignot

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ABSTRACT

The measurement capability of the Avionics Laboratory IR Facility was used to evaluate an absorption cell that will be used to simulate atmospheric absorption over horizontal paths of 1 - 10 km in length. Band models were used to characterize the transmittance of carbon dioxide (CO_2), nitrogen (N_2), and nitrous oxide (N_2O) in the cell. The measured transmittance was compared to the calculated values. Nitrous oxide is important in the 4 - 4.5 micron range in shaping the weak line absorption of carbon dioxide. The absorption cell is adequate for simulating atmospheric absorption over these paths.

SECTION I

INTRODUCTION

The Avionics Laboratory, Electronic Warfare Division, is developing an Infrared (IR) Threat Warning Receiver Concept Evaluation Facility to permit evaluation of currently deployed IR warning receivers and to evaluate new technical concepts in IR warning receiver design. To achieve this goal, the laboratory must be capable of simulating the spectral signatures of missiles and aircraft; therefore, it is necessary to represent the attenuation of the signatures due to atmospheric absorption through paths some kilometers in length. Since the IR active components of the atmosphere are present in only small amounts, one approach is to use an absorption cell containing high concentrations of the IR active species so that the optical thickness corresponds to that of a long atmospheric path.

The purpose of this project was to establish the limitations of using increased concentrations of IR active gases in an absorption cell for simulating the attenuation due to the atmosphere and to specify the required partial pressures of carbon dioxide, nitrous oxide and nitrogen for best simulation of atmospheric paths in the 2 - 5 micron region.

A. SUMMARY OF PROJECT

This project involved the following tasks:

1. Review atmospheric transmittance models and select one or more of these models to calculate the atmospheric transmittance over useful paths.

2. Measure the IR transmission through an absorption cell and develop experimental procedures for controlling the partial pressures of the atmospheric species in the cell.

3. Characterize the IR transmission through the partial pressures of the atmospheric species in the cell.

4. Characterize the IR transmission through the absorption cell by comparing the transmittance through the cell with the transmittance calculated by the selected atmospheric transmittance model.

B. APPROACH

The analytical phase of the project involved calculating atmospheric transmittance over operationally useful paths employing the standard models, LOWTRAN, and Aggregate[1,2]. Operationally useful paths were from .5 to 10 kilometers in length. Using these models, transmittance calculations over the short cell path length with varying amounts of carbon dioxide, nitrogen, and nitrous oxide in the cell were made to define ranges of partial pressures in which atmospheric simulations remain valid. The calculated transmittances then provided a basis of comparison with the measured data.

The experimental portion of the project entailed assembling and testing the gas-handling system for the cell and measuring the transmittance through the cell. The assembled gas-handling system permits filling the cell with known partial pressures of carbon dioxide, nitrogen, and nitrous oxide. The transmittance through the cell was measured from 2000 to 5000 cm^{-1} by a spectrometer with the cell filled with known mixtures of nitrogen and carbon dioxide.

SECTION II

ATMOSPHERIC TRANSMITTANCE MODELS

IR warning receivers are used to warn aircraft against tactical threats such as surface-to-air missiles and air-to-air missiles. Since these threats emit a very bright signature in the 2 - 5 micron region due to hydrocarbon combustion, warning receivers have a problem which is conceptually very simple to solve. However, many sources of IR radiation exist which are spectrally similar to tactical threats. In the 2 - 5 micron region, atmospheric absorbance occurs because IR active gases such as carbon dioxide, nitrous oxide, and carbon monoxide are part of the earth's atmosphere of gases. These gases occur naturally in concentrations of 330, .28, and .075 parts per million (PPM), respectively[2]. Absorption by carbon dioxide and nitrous oxide determines the spectral shape the IR target signatures will have in the 4 - 4.5 micron region. The band centers of carbon dioxide ($0\overset{\circ}{0}1-0\overset{\circ}{0}0$) and of nitrous oxide ($0\overset{\circ}{0}1-0\overset{\circ}{0}0$) are at 2349 cm^{-1} and 2224 cm^{-1}. The bands overlap and the absorption in this region is a mixture of nitrous oxide and carbon dioxide. The absorption by carbon monoxide occurs in this region but is not significant in determining the spectral shape since the concentration of CO in the atmosphere is less than that of nitrous oxide by a factor of 4 and the band strength is less by a factor of 5[8]. In the region of 4.5 - 5 microns, water vapor in the atmosphere becomes the dominant absorber. Water vapor and carbon dioxide are also the dominant absorbers in the 2 - 2.8 micron region. The 3 - 4 micron region has no absorbing gas and allows transmission of IR signatures with little or no absorption. However, because of the IR emission due to hydrocarbon combustion, the main region of interest in this report is absorption due to carbon dioxide in the 4 - 4.5 micron region.

Simulations of atmospheric absorption in the 4 - 4.5 micron region are possible using the absorption cell being developed by the Avionics Laboratory. However, the only way to validate the absorption cell simulations is to compare them to theoretical calculations or to actual field measurements. This project was limited to comparing the cell measurements to theoretical calculations. The atmospheric transmittance can be calculated using models and empirical techniques. The LOWTRAN model[1] and Aggregate models have been used to calculate the atmospheric transmittance for horizontal paths of .5 to 20 km.

A. LOWTRAN MODEL

LOWTRAN[1] is a FORTRAN computer code designed to calculate atmospheric transmittance and radiance for a known atmospheric path with a spectral resolution of 20 cm^{-1}. The code uses a single-parameter band model. The effects of continuum absorption, molecular scattering, and aerosol extinction are included in the calculation. LOWTRAN assumes that the mixing ratios of the carbon dioxide, nitrous oxide, methane, carbon monoxide, nitrogen and oxygen remain constant at all altitudes. The mixing ratios have the values 330, .28, 1.6, .075, 7.905×10^{-5}, and 2.095×10^{-5} PPM, respectively. LOWTRAN refers to these gases, with the exception of nitrogen, as the uniformly mixed gases. The total atmospheric transmittance generated by LOWTRAN includes the transmittances of the following gases: water vapor, uniformly mixed gases, ozone, nitrogen continuum, water vapor continuum, molecular scattering, and aerosols.

LOWTRAN is available on the ASD computer system and the transmittance data has been transferred to the Nicolet computer in the laboratory. The LOWTRAN calculations for comparison with the cell measurements were made using

the 1962 U.S. Standard Atmosphere over horizontal paths of .5, 1, 2, 3, 5, 7, 10, 15, and 20 kilometers and a spectral band of 2 - 5 microns. The haze model used in the calculation was "Rural extinction", 23 km visibility. Figure 1 shows the LOWTRAN calculations for the total transmittance for each range. Figure 2 shows the LOWTRAN calculations for uniformly mixed gases for different horizontal paths. The transmittance in Figure 2 includes effects of carbon dioxide as well as nitrous oxide and trace amounts of other gases.

B. AGGREGATE MODEL

The Aggregate method consists of a compilation of various models[2]. The models used for carbon dioxide and nitrous oxide were chosen to give the highest accuracy (5 cm^{-1} resolution) for each spectral region. The spectral transmittance is calculated by determining the atmospheric parameters and inserting them into formulae. The atmospheric parameters used in these calculations are the same as those used for the LOWTRAN calculation. All the Aggregate model calculations assume standardized, uniform atmospheric conditions in which the atmospheric pressure and the temperature along the path are constant at 760 mm Hg and 300°K, respectively. The Aggregate calculations have been used to validate the contributions of carbon dioxide and nitrous oxide to the atmospheric absorption in the 4 - 4.5 micron region calculated by LOWTRAN using the uniformly mixed gases.

1. Classical Elsasser Model for Carbon Dioxide (2245 - 2390 cm^{-1})

The transmittance for carbon dioxide was calculated using equation 5-66[2]. The average absorbance given by the integral in equation 5-66[2] was obtained by using Table I of an article by A. Zachor[3]. The transmittancescalculated using the Classical Elsasser Model are listed in Table I.

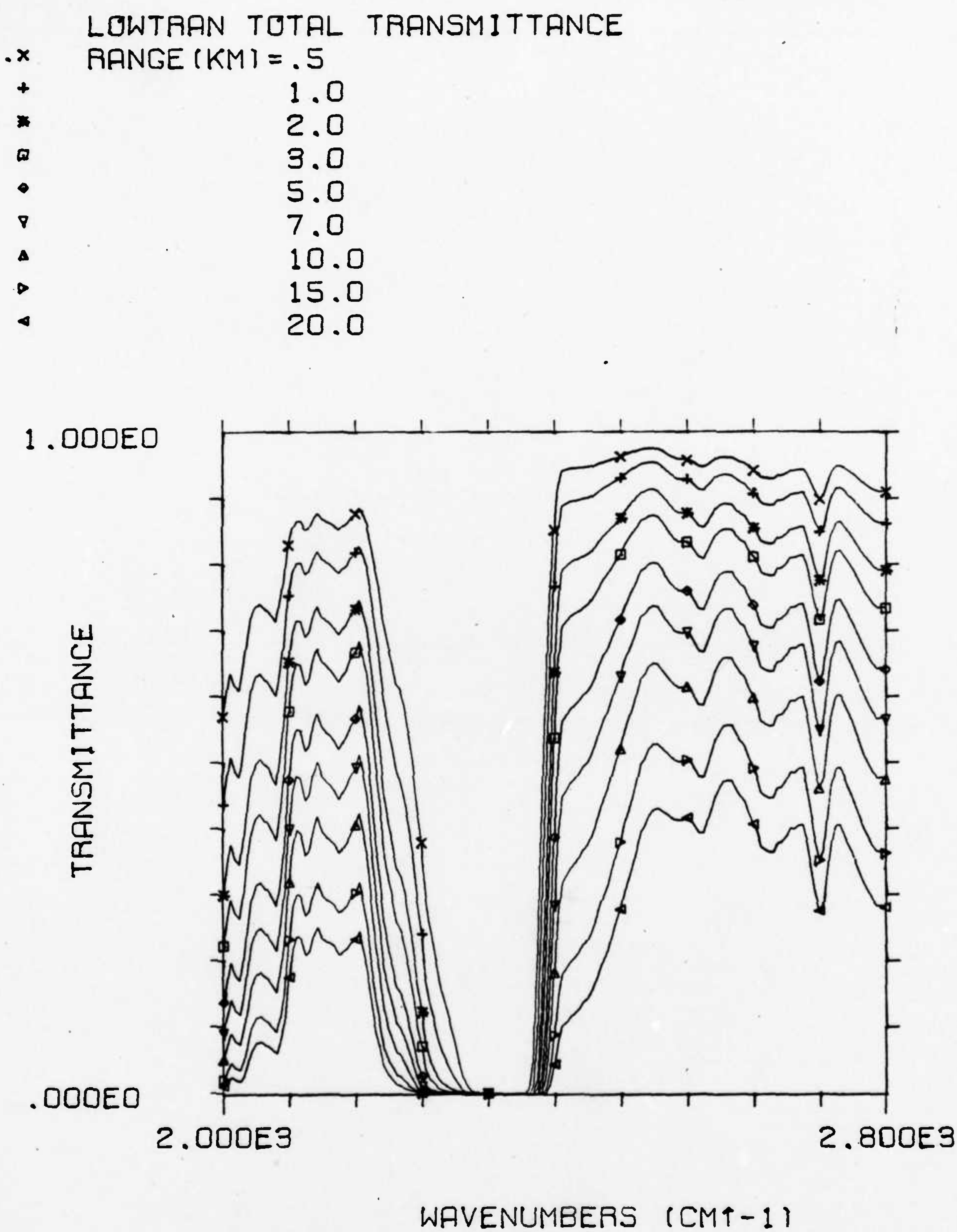

Figure 1. LOWTRAN Calculations, Total Transmittance

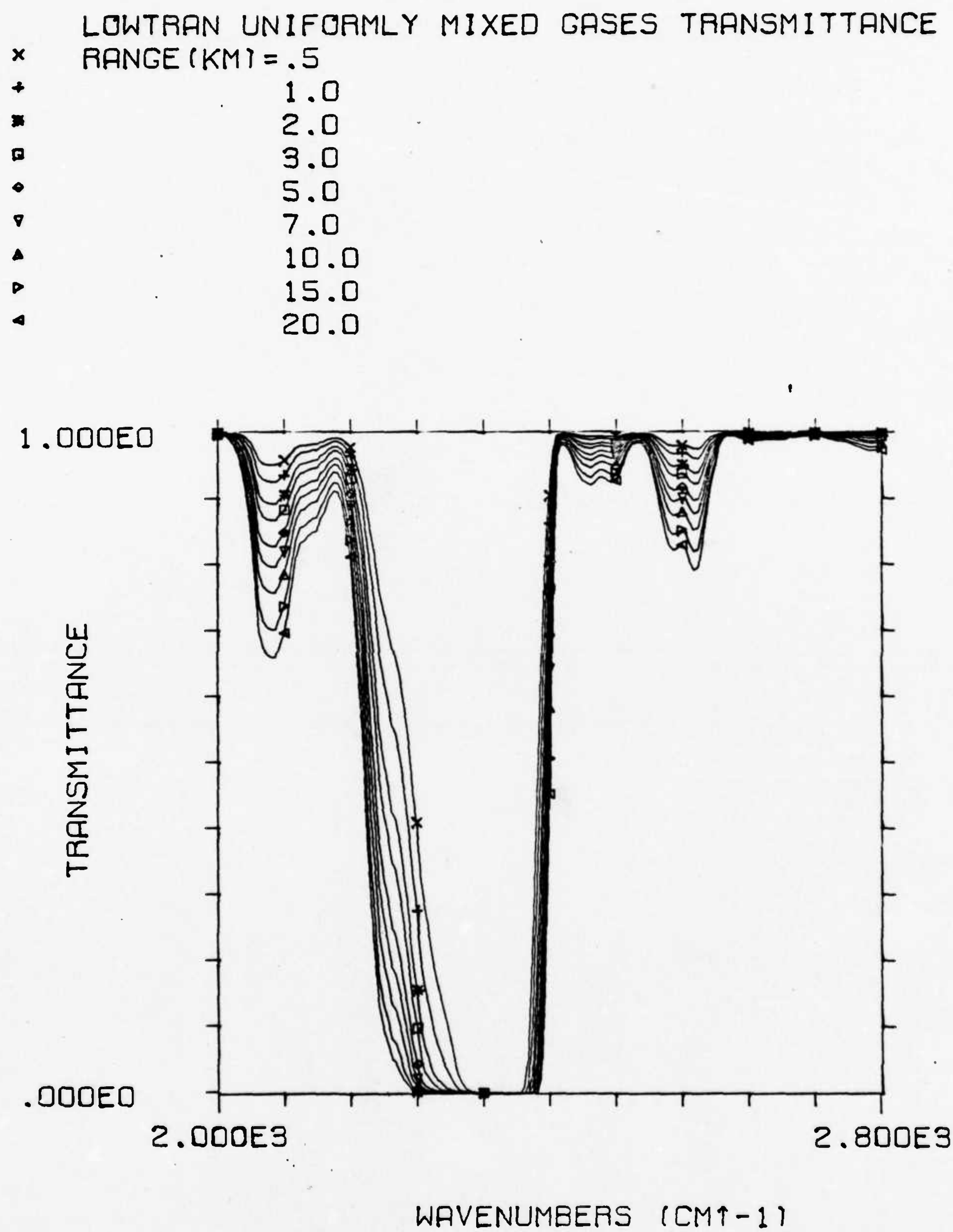

Figure 2. LOWTRAN Calculations, Uniformly Mixed Gases Transmittance

TABLE I. BAND MODEL CALCULATIONS FOR CARBON DIOXIDE

cm^{-1}	Transmittance (Range, km)				
	.5	1	2	3	5
2203	.992	.971	.963	.956	.931
2209	.985	.970	.957	.935	.915
2212	.969	.961	.932	.916	.880
2220	.932	.910	.848	.800	.674
2225	.883	.804	.667	.596	.473
2227	.838	.718	.587	.480	.389
2235	.750	.625	.468	.386	.275
2240	.575	.425	.270	.19	.14
2245	.41	.32	.08	.032	.0046
2250	.201	.09	.013	0.	0.
2255	.184	.066	.0056	0.	0.
2260	.174	.058	0.	0.	0.
2265	.1	.03	0.	0.	0.
2270	.092	.01	0.	0.	0.
2275	.064	.0078	0.	0.	0.
2280	.048	.0056	0.	0.	0.
2285	.030	.0025	0.	0.	0.
2290	.004	0.	0.	0.	0.
2295	0.	0.	0.	0.	0.
2380	.0007	0.	0.	0.	0.
2385	.0013	0.	0.	0.	0.
2390	.107	.0134	0.	0.	0.
2395	.638	.506	.346	.249	.136
2400	.984	.982	.971	.965	.956
2405	1.	.998	.9977	.997	.996

2. Empirical Model for Carbon Dioxide (2203 - 2240 cm^{-1})

The transmittance for carbon dioxide was calculated from equation 5-64[2]. The transmittances determined from Table 5-8[2] are listed in Table I. Figure 3 shows the band model calculations for carbon dioxide using the two approaches, Classical Elsasser and Empirical Model.

3. Strong-Line Elsasser Model for Nitrous Oxide (2114 - 2365 cm^{-1})

The transmittance for nitrous oxide was calculated from equation 5-18[2]. The calculated transmittances are listed in Table II for horizontal paths of .5, 1, 2, 3, 5, 7, 10, 15, and 20 kilometers. Figure 4 shows the calculated transmittances for each of these ranges.

C. MODEL COMPARISON

The Aggregate model calculations were made to determine the relative contributions of carbon dioxide and nitrous oxide and to establish the suitability of using LOWTRAN as a standard for comparison with the absorption cell measurements. The Aggregate model calculations for carbon dioxide give a transmittance greater than the LOWTRAN calculations in the 2200 - 2300 cm^{-1} spectral range (see Figures 2 and 3). However, this difference can be attributed to the presence of nitrous oxide in the LOWTRAN calculations. If the Aggregate model calculations for carbon dioxide and nitrous oxide are combined and compared with the LOWTRAN calculation, the Aggregate model and LOWTRAN model calculations of the transmittance are about equal. Figure 5 shows a comparison of the two models for a horizontal path of 1 km. The comparison shows that the absorbance by nitrous oxide is important in the region of 2200 - 2300 cm^{-1}. Even though the strongest absorber is carbon dioxide, the absorption by nitrous oxide changes the spectral shape and

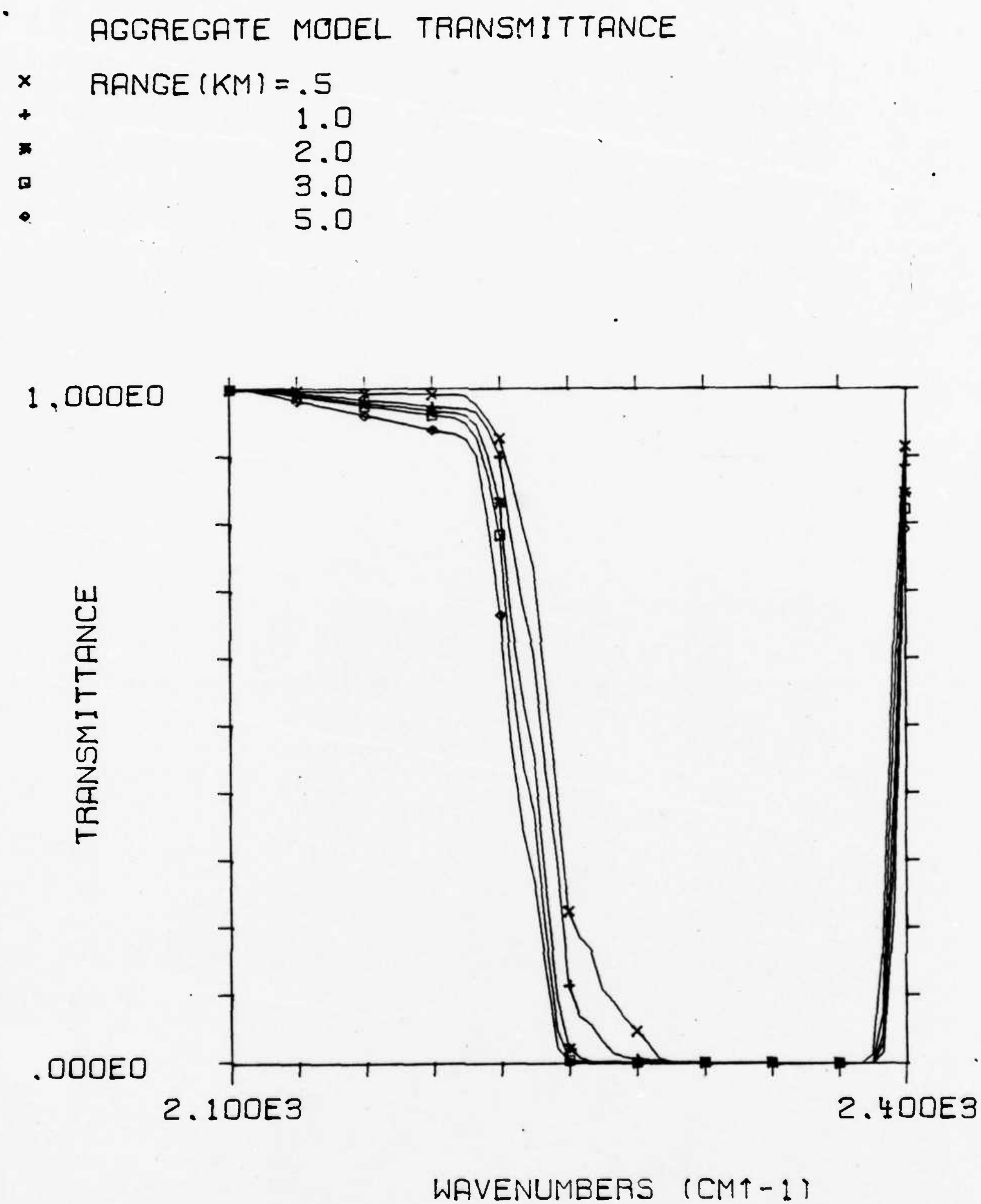

Figure 3. Aggregate Model Calculations for Carbon Dioxide

TABLE II. BAND MODEL CALCULATIONS FOR NITROUS OXIDE

cm^{-1}	Transmittance (Range, km)								
	.5	1	2	3	5	7	10	15	20
2114	1.	1.	1.	1.	1.	1.	1.	1.	.992
2128	1.	1.	1.	.991	.989	.985	.983	.98	.976
2146	.988	.986	.976	.971	.961	.953	.943	.93	.919
2174	.921	.888	.843	.808	.755	.707	.653	.582	.526
2186	.84	.78	.69	.63	.524	.453	.378	.28	.245
2199	.72	.62	.49	.4	.27	.192	.12	.056	.027
2203	.71	.6	.45	.37	.24	.164	.096	.0429	.019
2209	.74	.63	.5	.4	.28	.201	.127	.062	.031
2212	.74	.64	.51	.41	.29	.211	.135	.067	.035
2217	.74	.62	.51	.4	.27	.197	.123	.059	.029
2225	.71	.6	.46	.37	.24	.167	.099	.043	.02
2227	.7	.58	.44	.34	.22	.147	.082	.034	.014
2235	.67	.55	.4	.3	.18	.115	.06	.021	.008
2237	.74	.65	.52	.44	.32	.232	.153	.08	.043
2240	.8	.71	.61	.54	.42	.337	.252	.16	.105
2245	.88	.82	.76	.7	.62	.56	.486	.394	.323
2250	.926	.896	.854	.821	.773	.731	.68	.614	.56
2255	.952	.928	.904	.882	.848	.821	.788	.741	.702
2260	.971	.959	.942	.929	.909	.892	.876	.843	.821
2265	.982	.974	.964	.956	.944	.932	.919	.901	.888
2270	.989	.985	.979	.974	.967	.962	.953	.942	.932
2275	1.	1.	1.	.982	.978	.977	.97	.963	.957
2285	1.	1.	1.	1.	.989	-	-	-	-
2290	1.	1.	1.	1.	1.	.989	.985	.982	.979
2295	1.	1.	1.	1.	1.	.986	.983	.98	.975

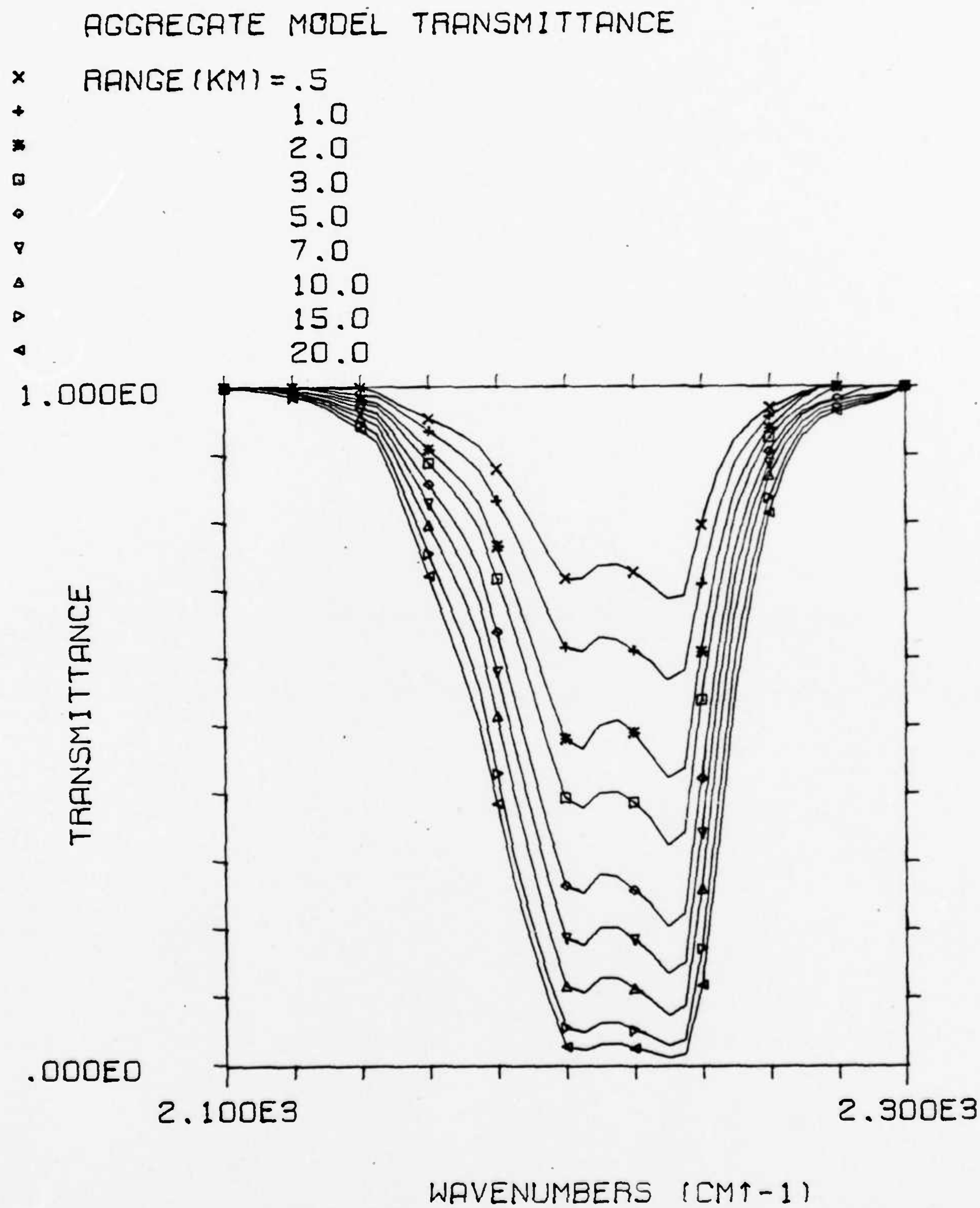

Figure 4. Aggregate Model Calculations for Nitrous Oxide

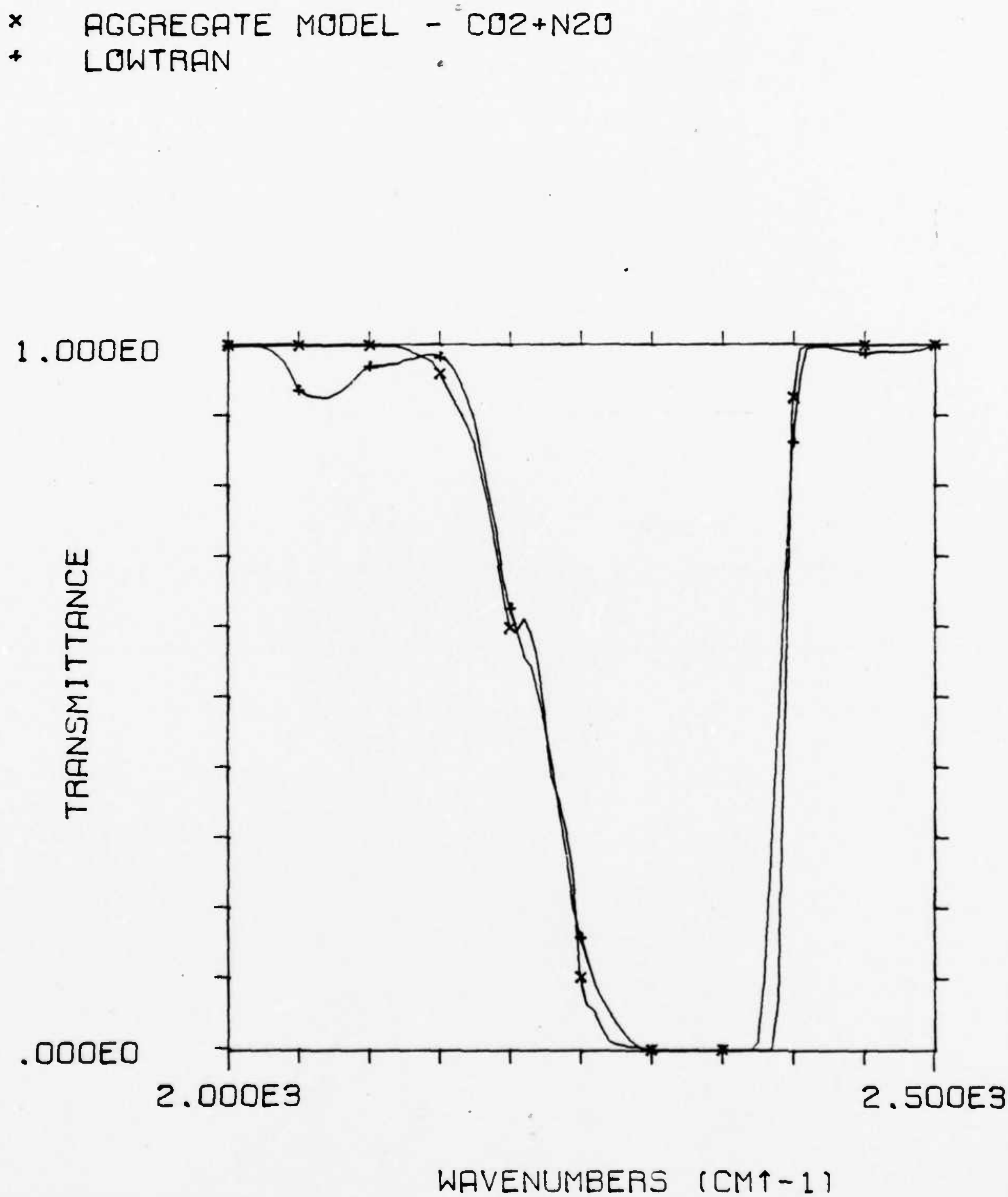

Figure 5. Comparison of LOWTRAN (Uniformly Mixed Gases) and Aggregate Model for a Horizontal Path of 1 km

causes substantial variation of the transmittance as a function of range. Therefore, nitrous oxide must be used in the absorption cell to permit reasonable simulations of absorption as a function of range.

SECTION III

EXPERIMENTAL APPARATUS

The experimental apparatus used in the measurements will be discussed in terms of three categories: (1) the absorption cell and gas-handling equipment, (2) the optical system, and (3) the spectrometer.

A. ABSORPTION CELL AND GAS-HANDLING EQUIPMENT

The absorption cell was designed and fabricated by Systems Research Laboratories, Inc. The optical configuration of the cell is shown in Figure 6. The front surface mirrors, M, are 6 inches in diameter, each having a focal length of 1 meter and a 1 inch diameter hole on the optical axis. The mirror surfaces are spherical to within a quarter wavelength in the visible region. The mirrors are mounted in Aerotech mirror mounts, Model AOM110-6. The optical axis of the cell passes through calcium flouride windows, W. At position B is a 1 inch diameter piece of cardboard mounted on a wire glued into the base-plate and used to block the single pass rays.

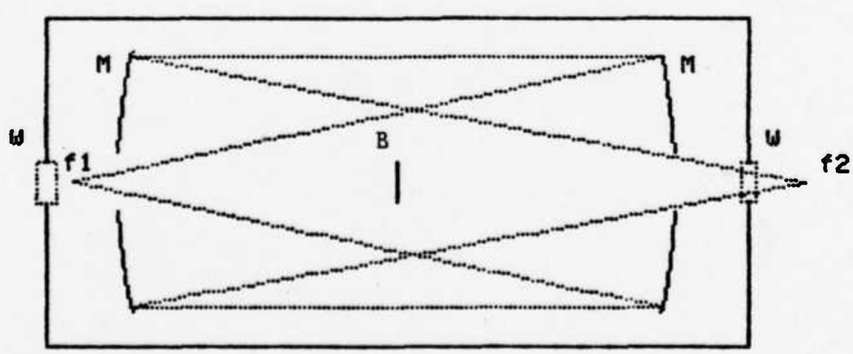

Figure 6. Optical Layout of Cell

The optics were aligned with the cell cover removed using a visible light point source placed at f1 and imaged at f2. The rays make three passes through the cell before arriving at f2. With the cell cover in place the optics in the cell are easily adjusted through access ports at each end of the cell.

The cell has a 1 inch thick aluminum baseplate with dimensions of 11.5 x 45.5 inches. The cover has dimensions of 44 x 10.5 x 10 inches and is made from 1/4 inch aluminum plate welded to form a rectangular shape with a 1 inch flange to mate with the baseplate. The cover has a vacuum/pressure gauge, pop-off valve, thermocouple gauge, and gas-handling plumbing mounted on it. The height of the cell above the optical table on which it sits is adjustable from 11.5 to 13.5 inches to allow alignment with optics external to the cell. The seal between the cover and baseplate is a 1/4 inch thick rubber gasket. The cover is fastened to the baseplate by 1/4-20 screws through the flange.

The gas-handling equipment consists of a Sargent Welch Model 1402 vacuum pump; 3/8 inch thick walled rubber hose; 1/2 and 1/4 inch swagelock valves, 1/4 inch copper tubing; a manifold; cold trap; and regulators for the carbon dioxide, nitrogen, and nitrous oxide cylinders. The vacuum pump is capable of evaluating the cell to approximately 100 millitorr of pressure. The cold trap consists of a 3/8 inch copper tubing coil in a dewar cooled with liquid nitrogen and keeps the pump oil vapor from entering the cell and manifold as they are evacuated. The manifold consists of a valve and tubing network used to control the filling of the cell with gases. The manifold also has a thermocouple pressure gauge attached to it. Figure 7 shows the absorption cell and gas-handling equipment.

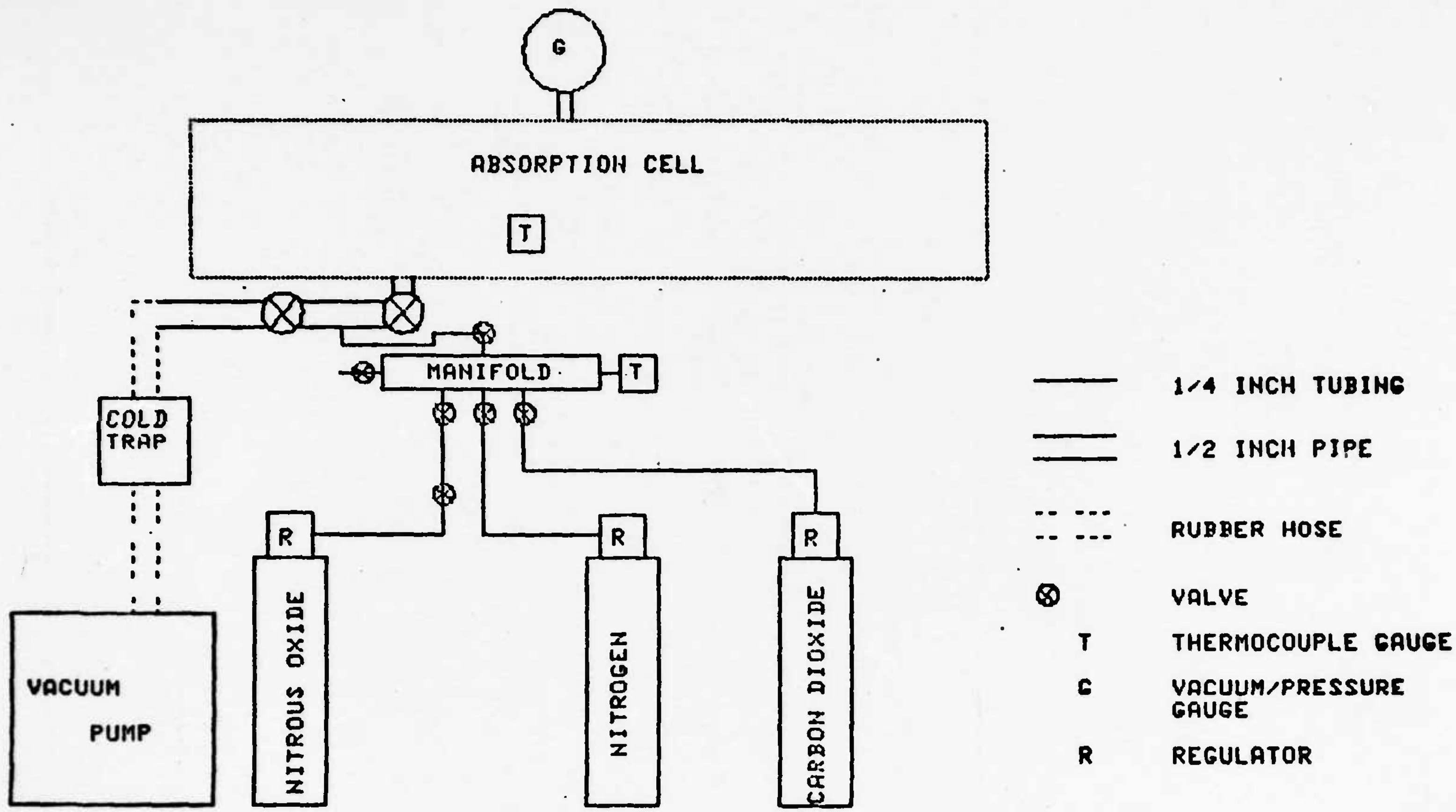

Figure 7. Absorption Cell and Gas-Handling System

B. OPTICAL SYSTEM

The optical system consists of the optics connecting the blackbody to the cell and the optics connecting the cell to the spectrometer. Figure 8 shows the optical layout. Mirror M1 is a front surface spherical mirror of focal length f = 11.8 inches. Mirrors M2 and M3 are plane front surface mirrors used to fold the radiation into the cell. Shutter, S, is controlled by the computer and is used to block the blackbody for the background measurements.

The optical system connecting the cell to the spectrometer consists of mirrors M4, M5, and a Davidson Optronics 16" collimator and is fully described in reference 4.

Since all the connecting optics use off-axis techniques of radiation transfer, optical aberrations can become a significant problem. Reference 4 addresses this issue and concludes that the effect of the divergence caused by aberrations on the output of the collimator is small compared to the effect of a finite source. Therefore, the aberrations due to this connecting optical system can be neglected.

C. THE SPECTROMETER

The AFWAL spectrometer consists of a high resolution (.64 cm^{-1}) Michelson interferometer operating at liquid nitrogen temperatures and connected to a minicomputer. The interferometer was constructed for airborne measurements by Block Engineering under the name "Phoenix Interferometer". The interferometer specifications are summarized in Table III. Additional information concerning this interferometer is contained in the instruction manuals "Phoenix Spectrometer System" and "Firebird Spectrometer System"[5,6].

A Nicolet 1180 minicomputer is used to process the interferometer output. Nicolet Instrument Corporation developed a computer program named FTIR to

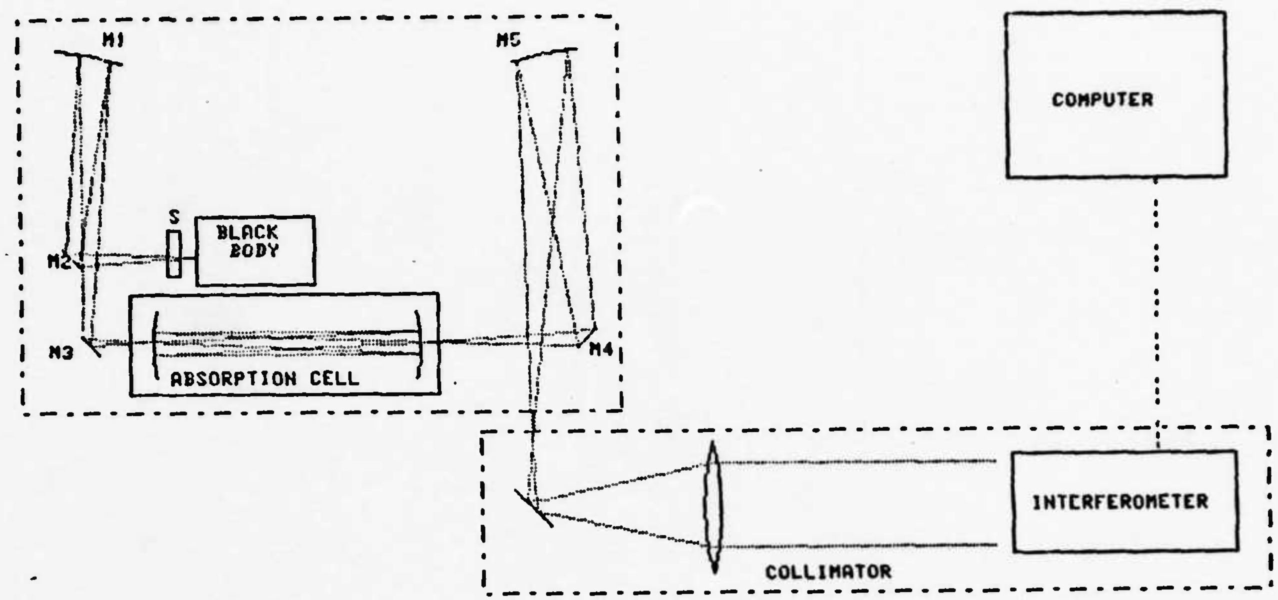

Figure 8. Optical System

TABLE III. INTERFEROMETER SPECIFICATIONS[5,6]

Spectral Range (μm)	2 - 5.5
Nominal Resolution (cm^{-1})	0.64
Retardation (cm)	1.56
Retardation Rate (cm/sec)	5
Sample Interval (μm)	0.95
Detector	InSb
Temperature (degrees K)	77
Cryogen Hold Time (hrs)	~6
Instrument	
Field of View (full angle, mrad)	5.6
Collecting Optics Diameter (cm)	10

make spectral measurements easily using the "Block type" of interferometer. FTIR allows the interferometer operator to make both absolute radiometric and transmittance measurements. The software is completely documented in the Nicolet manuals[7].

SECTION IV

EXPERIMENTAL PROCEDURE

Since the cell measurements required that the optics external to the cell be in alignment, gas-handling procedures be specified, and transmittance measurement techniques be consistent, only these experimental procedures will be described in the following sections.

A. OPTICAL ALIGNMENT

The procedures used to align the cell were described in Section II.B. The most difficult procedure involved aligning the collimator with the optics between the blackbody and collimator. These tasks were accomplished using a low power HeNe laser and autocollimating telescope. The autocollimating telescope was first aligned with the 16 inch collimator and focused on the collimator's focal point. The laser was then co-aligned with the telescope. The source point of Figure 8 was then aligned with the telescope and laser using procedures described in reference 4. A .125 inch aperture was placed at the source point and the laser used as a reference beam through the cell. With a point source replacing the blackbody of Figure 8, mirrors M1, M2, and M3 and the cell were adjusted until the laser illuminated the point source. At this point the optical system was coarsely aligned. Then, using the telescope and point source, the same procedure was repeated to assure alignment of the system.

To assure f2 in Figure 6 of being external to cell, f1 had to be positioned between the cell window and the mirror, M, in the cell. This was done by moving the point source and M1 along the optical axis closer to the cell.

The image of the point source through the cell was then co-aligned with the .125 inch aperture. Again the system alignment was verified using the telescope and point source.

B. GAS-HANDLING PROCEDURES

One of the major problems encountered early in this project was isolating and stopping leaks in the vacuum system. Finally, after replacing the pump lines and swagelock fittings with the 3/8 inch thick walled rubber hose and the cell gaskets with thicker 1/4 inch gaskets, the cell could be evacuated to 100 millitorr. After closing the main valve to the cell, slow leaks caused the pressure to increase to 500 millitorr in one hour. Pressures higher than 500 millitorr cannot be measured with the thermocouple gauge. However, a one-hour hold time was adequate for making empty cell measurements and filling the cell with artificial atmospheres.

The procedure used in pumping and filling the cell was a three step process. First, the cell was pumped through the cold trap to 100 - 200 millitorr and sealed off. The gas manifold and gas lines were then pumped down to pressures in the same range and sealed off. After making empty cell measurements, known quantities of gases were released into the cell in ascending order of the partial pressures of the gases. This method causes faster mixing of the gases and flushes the gas lines of active gases. As will be shown later, the active gas, nitrous oxide, must be used in the cell to accurately simulate atmospheric absorption in the 2500 cm^{-1} region. After the gas mixture had been released into the cell and the cell sealed off, a wait of 3 - 5 minutes was necessary to allow the gas mixtures to reach equilibrium. At this point the full cell measurement was made.

The partial pressures of the gases in the cell were measured directly using the relative pressure/vacuum gauge on the cell or by filling a small known volume to a calculated pressure and then releasing this gas into the cell. The pressure in the small volume was calculated using the Gas Law. The partial pressures of both nitrogen and carbon dioxide were measured using the first method. Since the quantity of nitrous oxide required in the cell was so small, the second procedure had to be used to measure the partial pressure accurately.

Since the active gas, nitrous oxide, is required in the cell to simulate atmospheric absorption accurately, approval of the Avionics Laboratory safety office had to be obtained before nitrous oxide could be used in the cell. Since the quantity of nitrous oxide vented into the laboratory was no more than .005 g moles, approval was granted on the condition that strict operation procedures be used in filling the cell with nitrous oxide. In the case of uncontrollable nitrous oxide leaks, emergency laboratory and building evacuation plans must be followed.

C. MEASUREMENT PROCEDURES

The transmittance measurements were made using software routines written with FTIR. This program prompts the operator during the measurements to ready the cell and automatically measures and calculates the cell transmittance. The transmittance is then labeled and stored in disk memory.

The algorithm ratios the spectrum obtained with the cell full of gas to the spectrum obtained with the cell evacuated using equation (1).

$$T = 100 * \frac{S_2 - B_2}{S_1 - B_1} \qquad (1)$$

where

S_2 = full cell spectrum

B_2 = full cell background spectrum

S_1 = empty cell spectrum

B_1 = empty cell background spectrum

T = transmittance (%)

The background spectra are obtained by blocking the blackbody radiation through the cell with a shutter and collecting the data from the interferometer. This technique subtracts the interferometer self radiation and the 300°K radiation from the laboratory from the transmittance measurement, making it unnecessary to use an instrument response function.

SECTION V

MEASUREMENTS

Using the measurement procedures described in Section IV, transmittance measurements through the absorption cell were made using various partial pressures of carbon dioxide, nitrogen, and nitrous oxide. The artificial atmospheres in the cell used for these measurements are summarized in Table IV. Figures 9 through 12 show plots of the cell transmittance versus wavenumber (cm^{-1}) for measurements 1, 17, 21, and 25. The plots are limited to the 2000 - 2800 cm^{-1} region. However, the data stored in the computer cover the complete bandwidth of the interferometer. The region from 2310 - 2380 cm^{-1} is not plotted due to division by zero in the transmittance calculations. Measurements 1 - 4 and 6 - 10 were made to determine the effect of various partial pressures of carbon dioxide in the cell. Measurements 20 - 28 were made to characterize the absorption of nitrous oxide in terms of partial pressures. Four of the measurements (5, 17, 18, and 19) were made with only nitrogen in the cell to determine the effect of evacuating the cell on the optical alignment. Measurements 7 - 9 and 13 - 16 were made to determine the effect of pressure broadening and to find the limitations of the absorption cell. Plots of the remaining measurements are shown in the appendix.

TABLE IV. MEASUREMENT CHARACTERISTICS

NO.	PARTIAL PRESSURE (PSI)			FIGURE
	CO_2	N_2	N_2O*	
1	4	25	-	9
2	9	20	-	A1
3	14	15	-	A2
4	19	10	-	A3
5	-	1 ATM	-	A4
6	1 ATM	-	-	A5
7	2	27	-	A6
8	1	28	-	A7
9	.5	28.5	-	A8
10	4	5	-	A9
11	4	10	-	A10
12	4	15	-	A11
13	4	20	-	A12
14	4	27	-	A13
15	4	29	-	A14
16	4	31	-	A15
17	-	31	-	10
18	-	33	-	A16
19	-	35	-	A17
20	-	~1 ATM	6	A18
21	-	~1 ATM	50	11
22	-	~1 ATM	17.5	A19
23	-	~1 ATM	25	A20
24	-	~1 ATM	40	A21
25	2	27	15	12
26	9	20	25	A22
27	14	15	55	A23

*Pressure in tubing external to cell

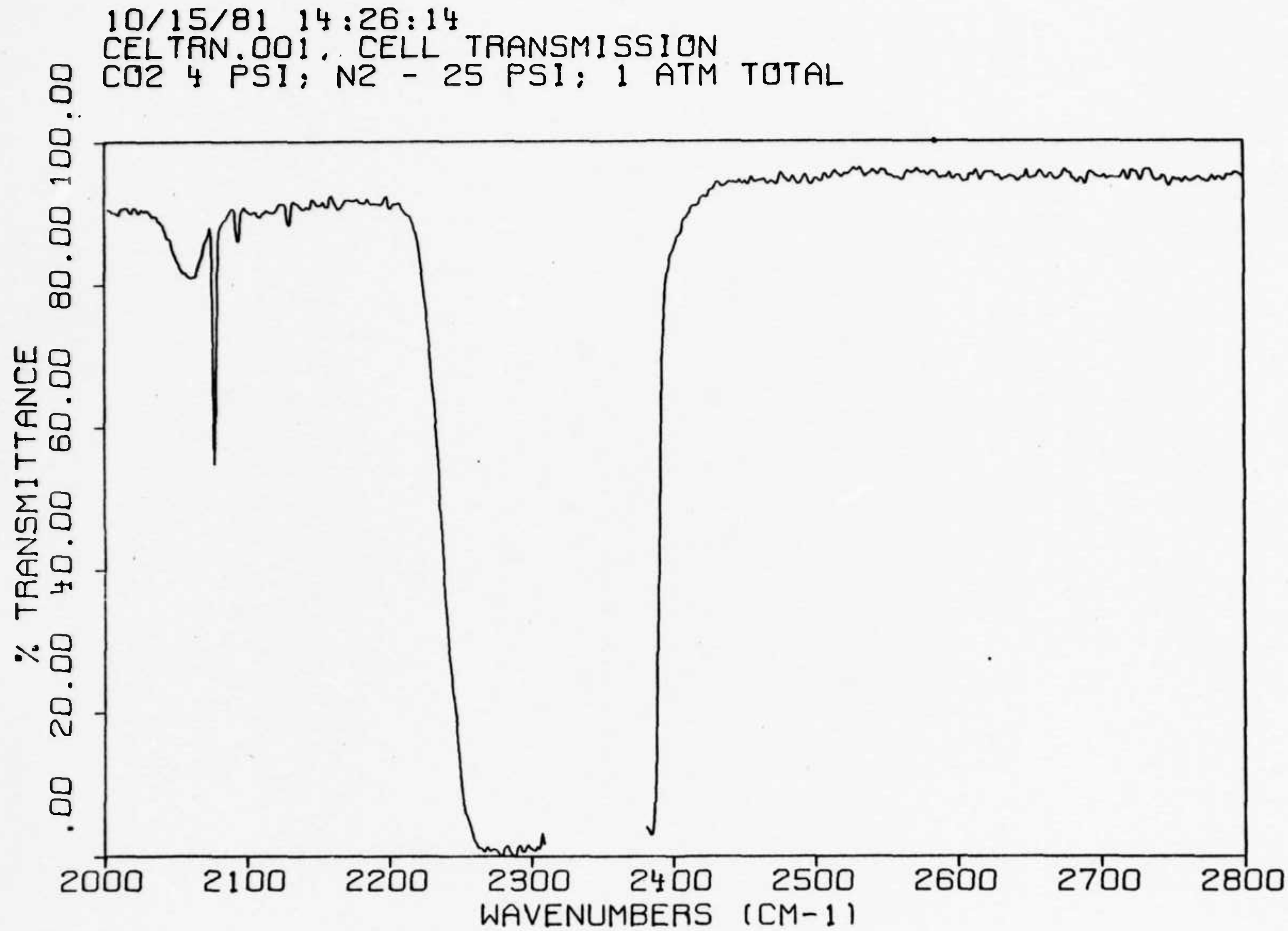

Figure 9. Measurement Number 1

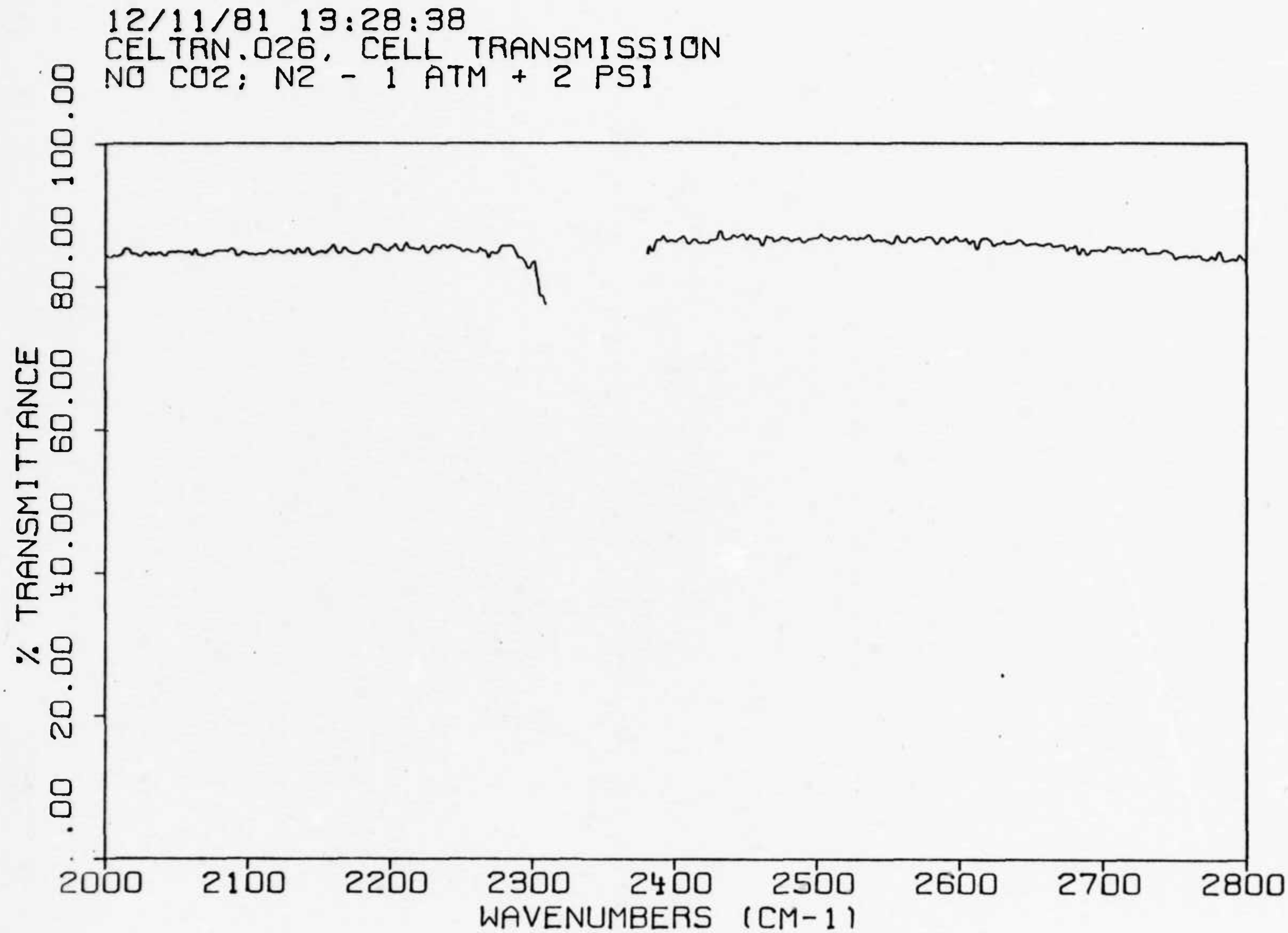

Figure 10. Measurement Number 17

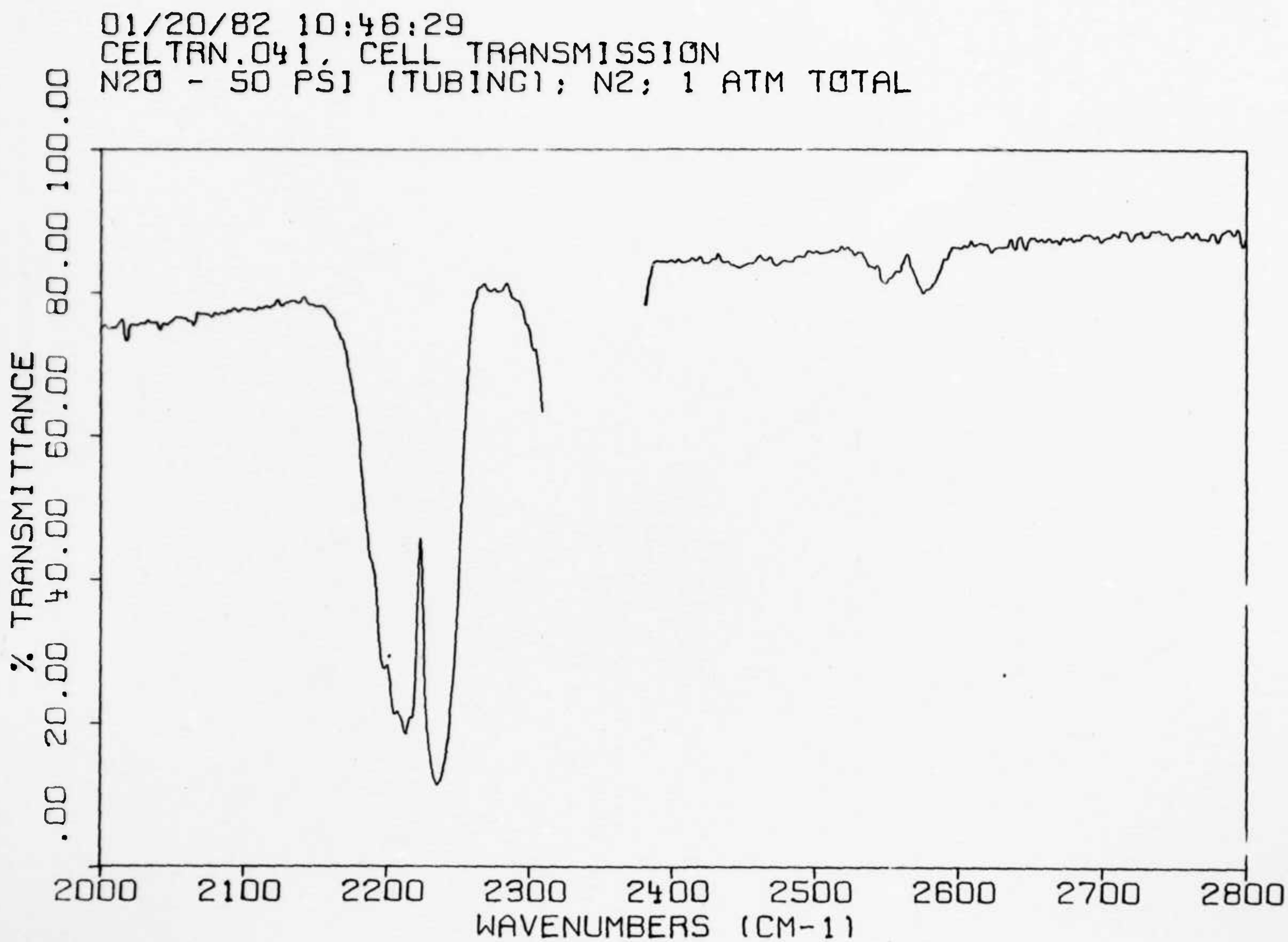

Figure 11. Measurement Number 21

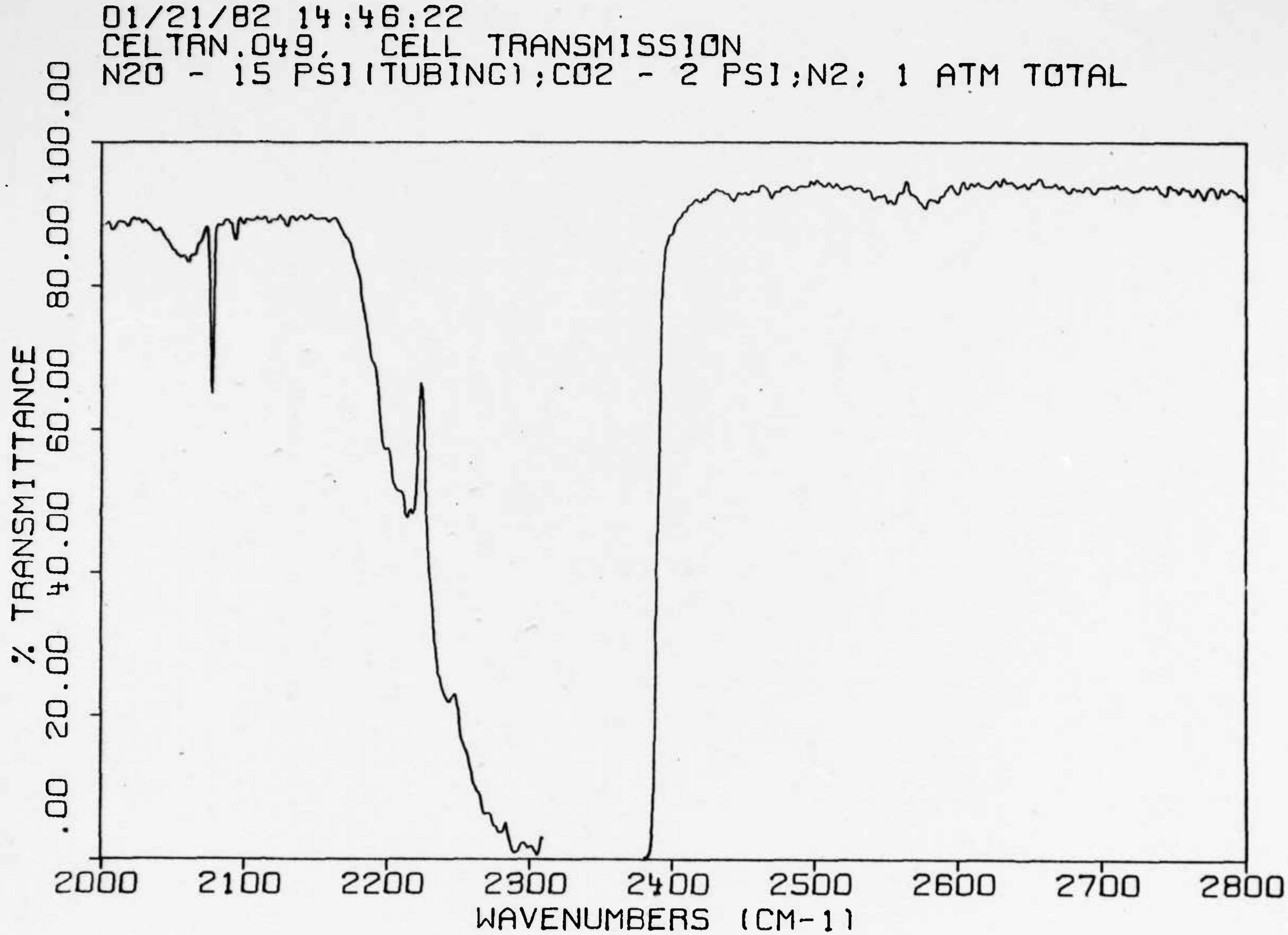

Figure 12. Measurement Number 25

SECTION VI

RESULTS AND ANALYSIS

As expected, increasing the partial pressure of carbon dioxide in the cell resulted in more absorption in the carbon dioxide bands. However, the absorption by nitrous oxide is important in developing a good simulation of atmospheric absorption using the cell. Absorption by nitrous oxide in the 2222 - 2500 cm^{-1} region affects the shape of the red side of the carbon dioxide band enough to cause substantial variation with the partial pressure of nitrous oxide. The partial pressure of nitrous oxide in the cell can be established accurately enough to permit range simulations to within a kilometer assuming a nonpolluted standard atmosphere. This is not the case with measuring the partial pressure of carbon dioxide. Since the carbon dioxide band strength (in units of cm^2/molecule/cm) is so much greater than that of nitrous oxide (10^{-8} for CO_2 and 5×10^{-17} for N_2O[8]), the absorption by carbon dioxide near the band center (2245 - 2390 cm^{-1}) is nearly 100%. Therefore, only the weak lines (2200 - 2245 cm^{-1}) of carbon dioxide contribute significantly to the spectral shape. Carbon dioxide becomes transmissive at ranges of less than 1 km in the 2245 - 2280 cm^{-1} region and contributes to the shape. However, the region of contribution is narrow and only slightly modifies the spectral shape.

A. EFFECT OF EVACUATING THE CELL ON OPTICAL ALIGNMENT

During the alignment of the optical system, before making any measurements, a point source was focused through the cell and the image observed while the cell was pumped down. The image moved 1/16" vertically during the pumping, indicating that the alignment was changing. No measurement of the

change was recorded since the image returned to the original point as the cell was pressurized. Since the mirrors and mounts are attached directly to the cell baseplate, any movement of the baseplate will cause a misalignment of the optics. Therefore, the image movement can be attributed to movement of the baseplate as the cell is evacuated. The effect that this misalignment has on the cell measurements can be seen if the measurements are normalized by dividing by a cell measurement with the cell containing only nitrogen and comparing the original measurement with the normalized transmittance. Nitrogen was used to show this effect because nitrogen is transmissive in the 2 - 5 micron region. However, the measurements of nitrogen in the cell show a variation in the transmittance over this spectral range. In fact, the transmittance varies with the total pressure. Figure 13 shows the variation of transmittance for different total pressures of nitrogen. The total variation is about 17% in the 2000 - 2200 cm^{-1} region for nitrogen pressures of 1 ATM, 31, 33, and 35 PSI. Figure 14 shows a comparison of a cell measurement with the normalized measurement. In this case, the variation is less than 10%. Since the misalignment of the cell causes a significant change in transmittance, all the measurements have been normalized and both cell transmittance curves will be used in the remaining discussion. The misalignment effect of the cell will not be important for atmospheric absorption simulations since the cell will be filled with a known atmosphere and only the absorption by the atmosphere through the cell will be simulated. The cell will be used only at pressures near 1 ATM where the cell is aligned correctly.

B. ABSORPTION CELL CHARACTERIZATION

For simulations of atmospheric absorption in the 4 micron band of carbon dioxide, increasing the partial pressure of carbon dioxide caused increased

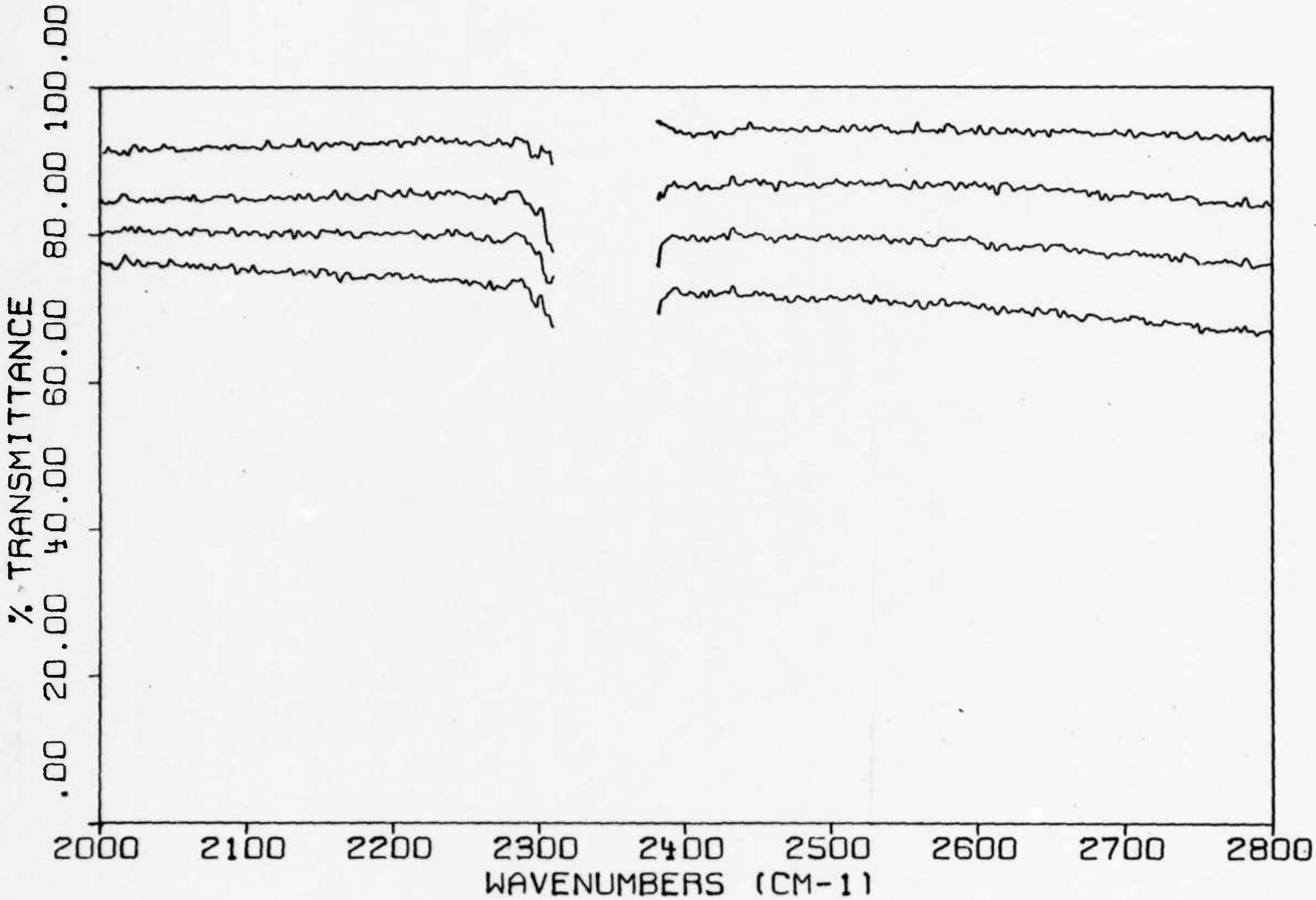

Figure 13. Variation of Transmittance for Nitrogen Total Pressures of 1 ATM, 31 PSI, 33 PSI, and 35 PSI

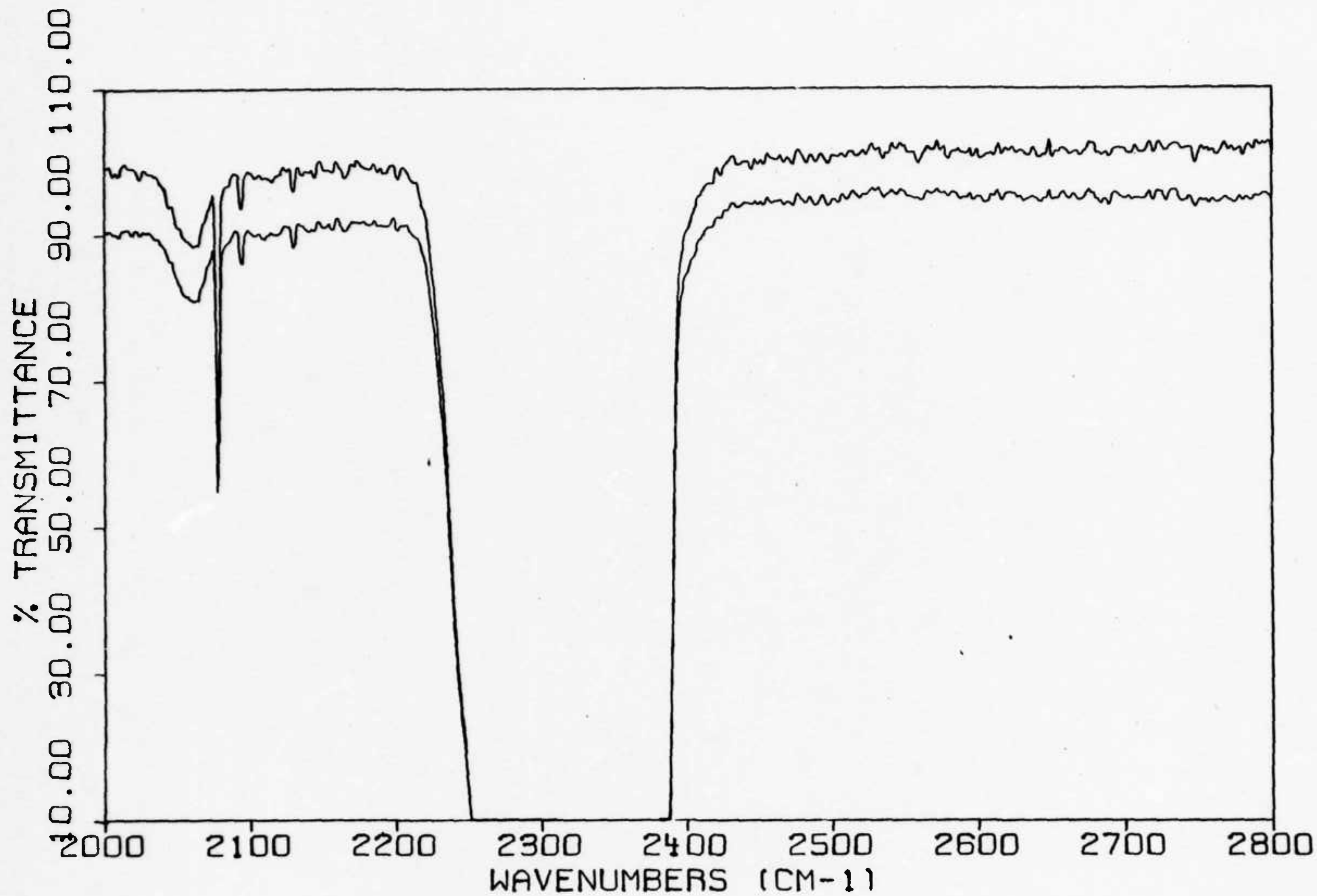

Figure 14. Comparison of Cell Measurement with Normalized Measurement for a Carbon Dioxide Partial Pressure of 4 PSI

absorption. The highest partial pressure of carbon dioxide used in the cell was 1 ATM and the lowest partial pressure was .5 PSI. Figure 15 shows the variation of absorption by carbon dioxide as a function of the partial pressure. This gauge measures pressure relative to the barometric pressure. A reasonable estimate of the repeatability of filling the cell with carbon dioxide is ± 1 PSI. Therefore, measurements that used partial pressures of carbon dioxide of less than 2 PSI can be considered only empirically as showing the proper trend.

The effect of pressure broadening of carbon dioxide by nitrogen is not important in the measurements since the band model calculations include the effect of pressure broadening and the measurements compare well with these calculations, which will be shown later. If the measurements are made with a resolution of .64 cm^{-1}, the individual lines of carbon dioxide can be resolved and more analyses of the effect of pressure broadening can be performed. However, measurements with 4 PSI of carbon dioxide and various partial pressures of nitrogen can be used to show the repeatability of the gas-handling system. In measurements 1 and 10 - 16, carbon dioxide was emitted into the cell only twice. Measurements 10 - 16 were made by making one background measurement and using it for the whole series. Therefore, only nitrogen was added to the cell atmosphere between measurements. In Figure 16 the absorption by carbon dioxide is about the same in the absorption band for each measurement. However, the variation in transmittance out of band is caused by the misalignment effect previously discussed.

Comparison of the cell measurements with the LOWTRAN calculations show good agreement in the strong line region of carbon dioxide. See Figures 17 to 21. However, the effect of nitrous oxide must be included to allow comparison of the measurements with LOWTRAN calculations. Therefore, using these

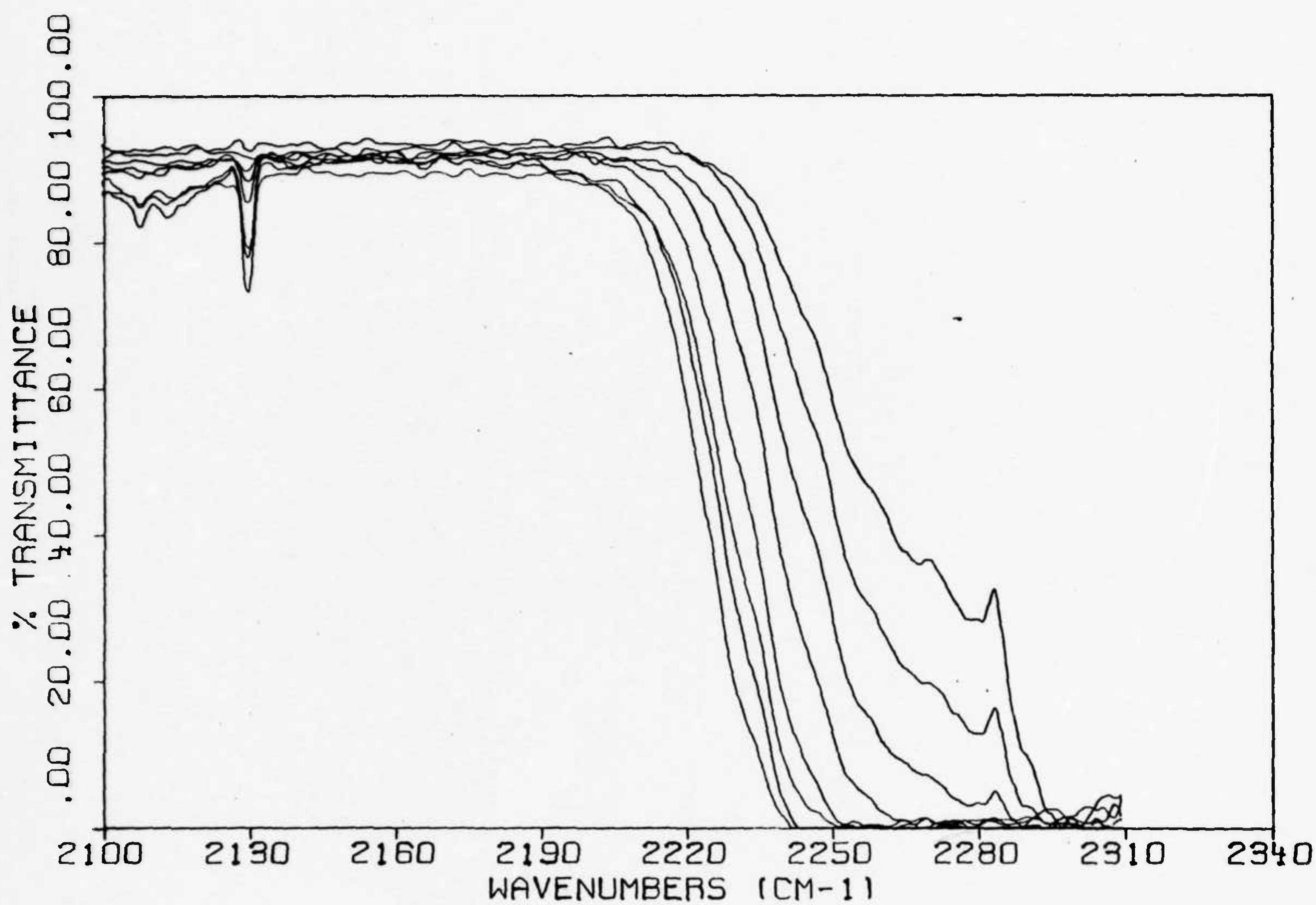

Figure 15. Comparison of Absorption by Carbon Dioxide as a Function of the Partial Pressure (Measurements 9, 8, 7, 1-4, 6 in increasing order of partial pressure)

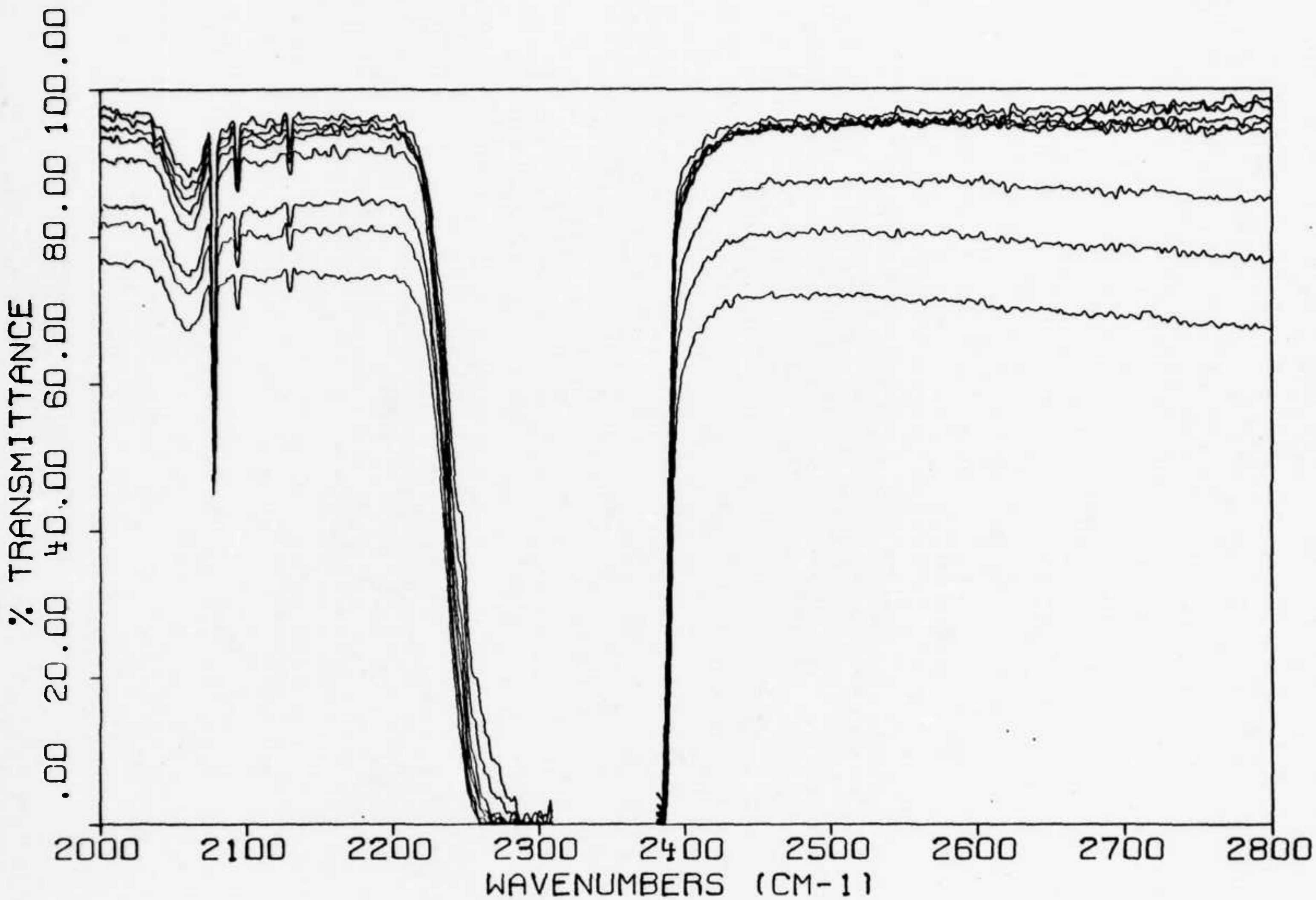

Figure 16. Comparison of Measurements with Equal Pressures of Carbon Dioxide (4 PSI)

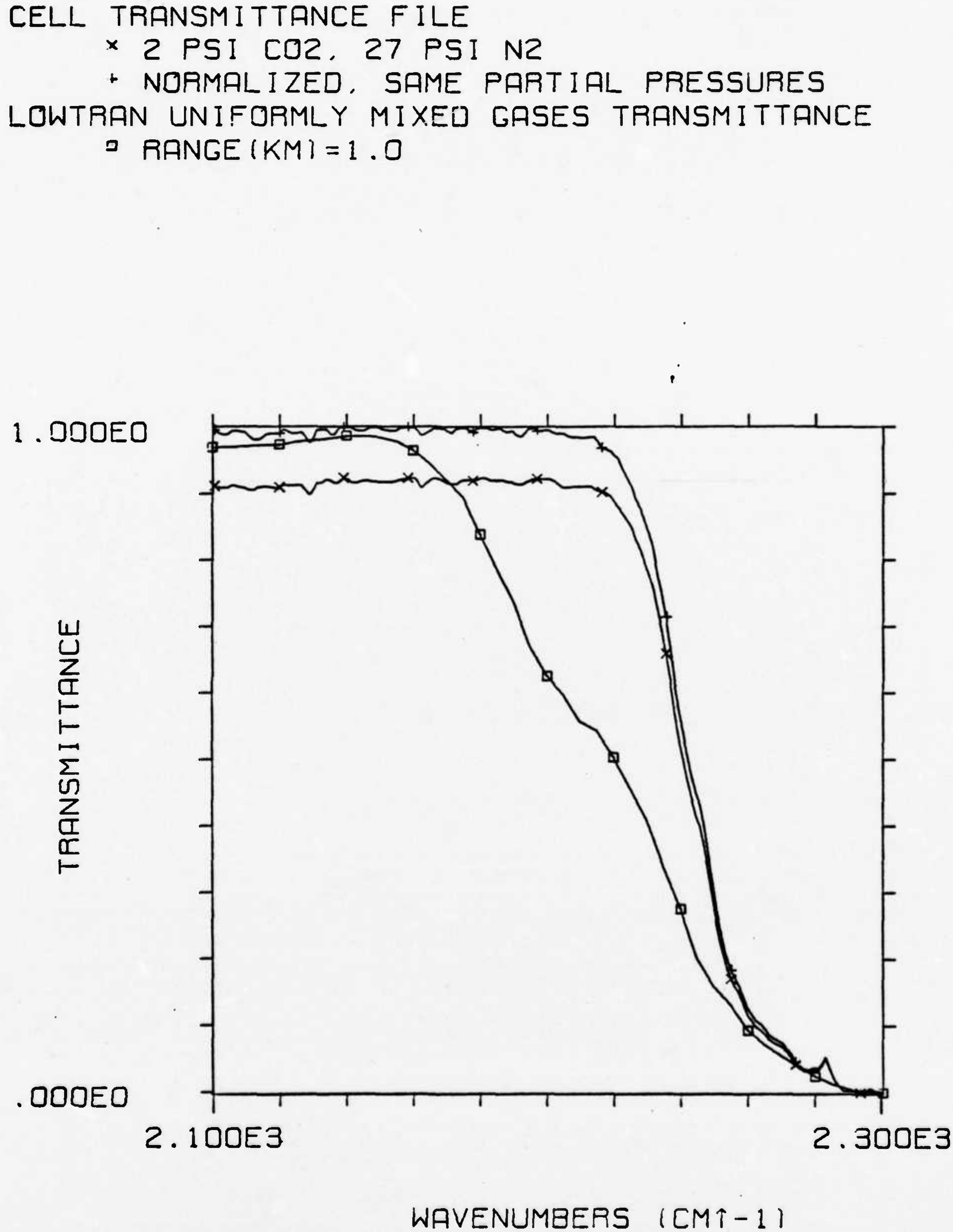

Figure 17. Comparison of Measurement 7 with LOWTRAN

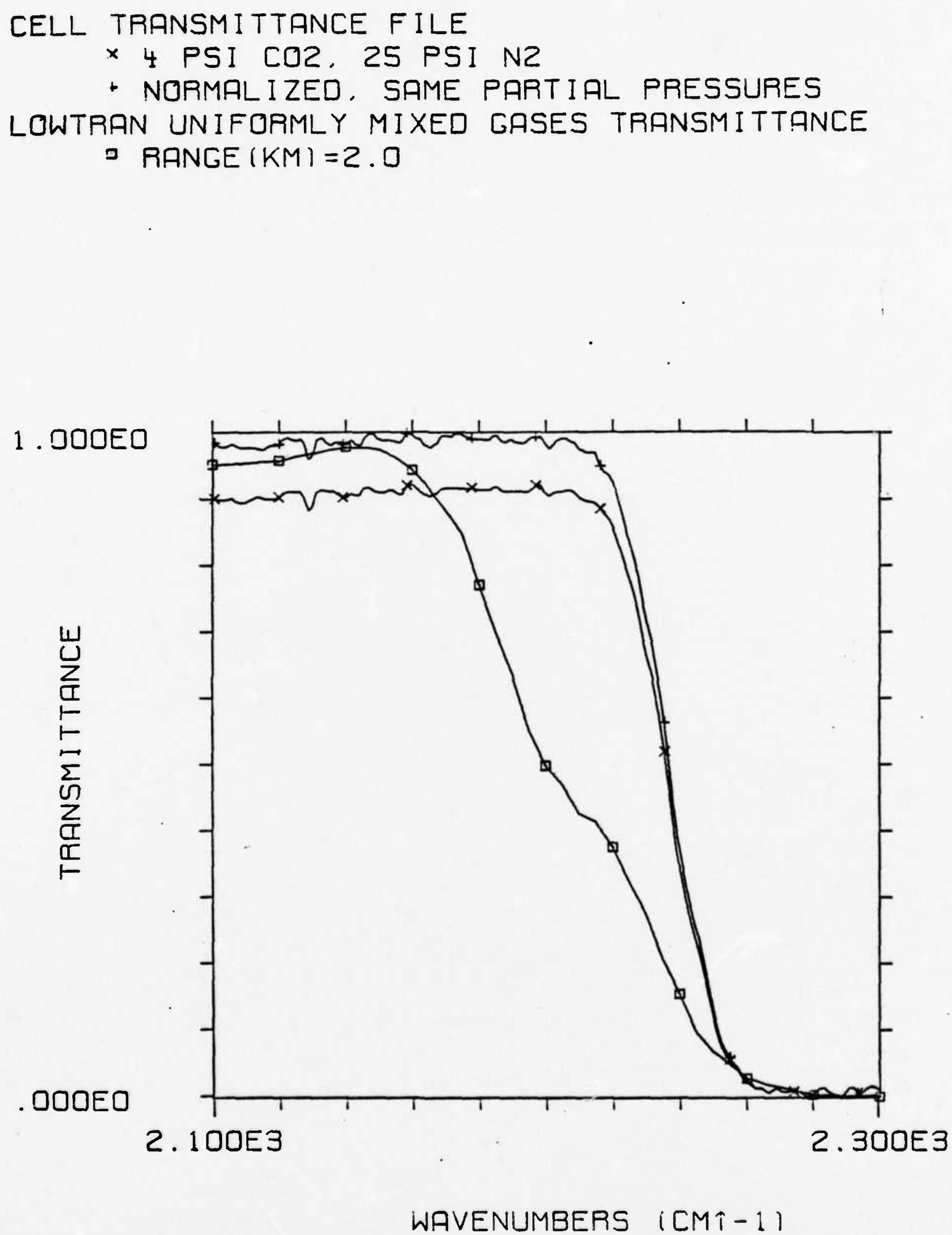

Figure 18. Comparison of Measurement 1 with LOWTRAN

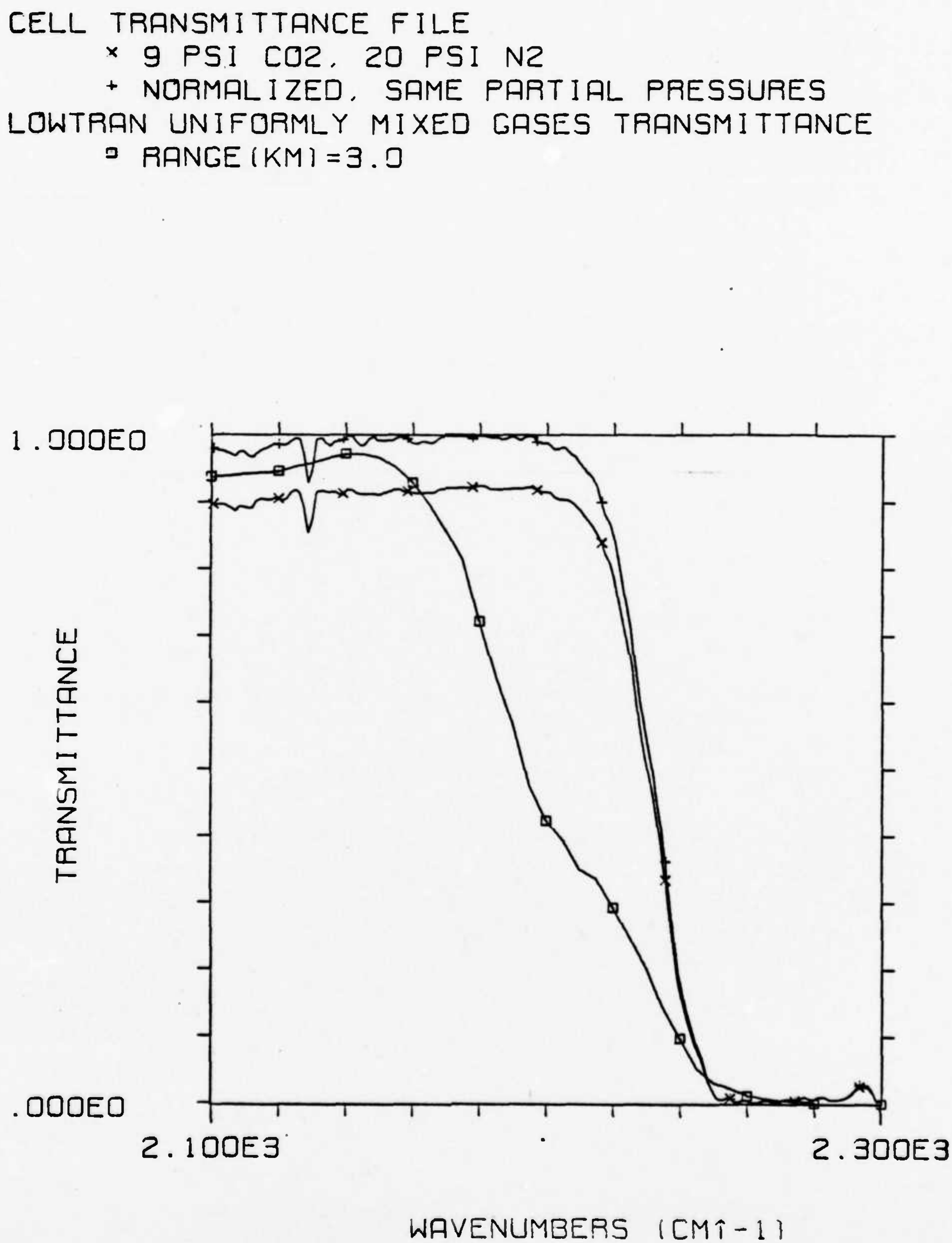

Figure 19. Comparison of Measurement 2 with LOWTRAN

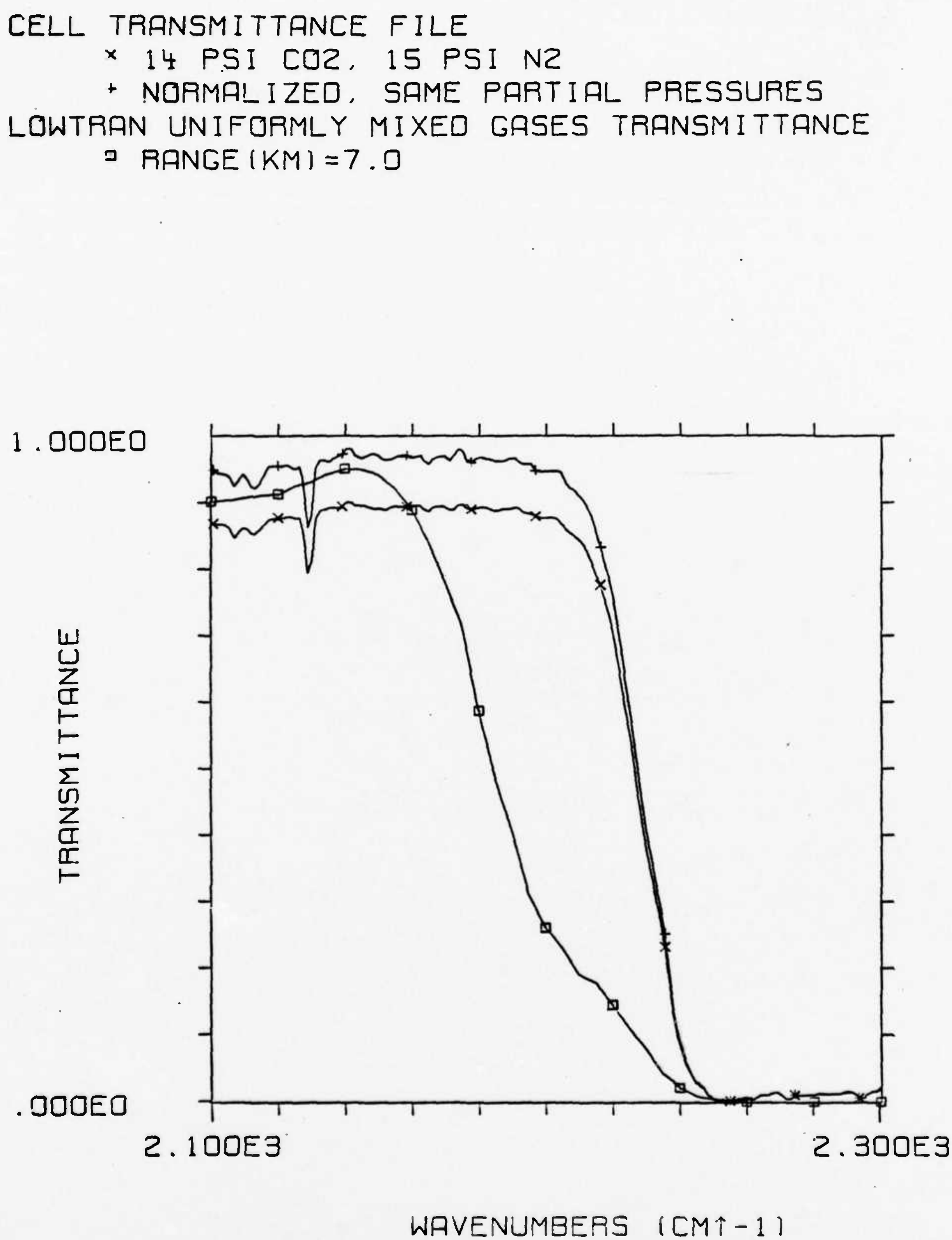

Figure 20. Comparison of Measurement 3 with LOWTRAN

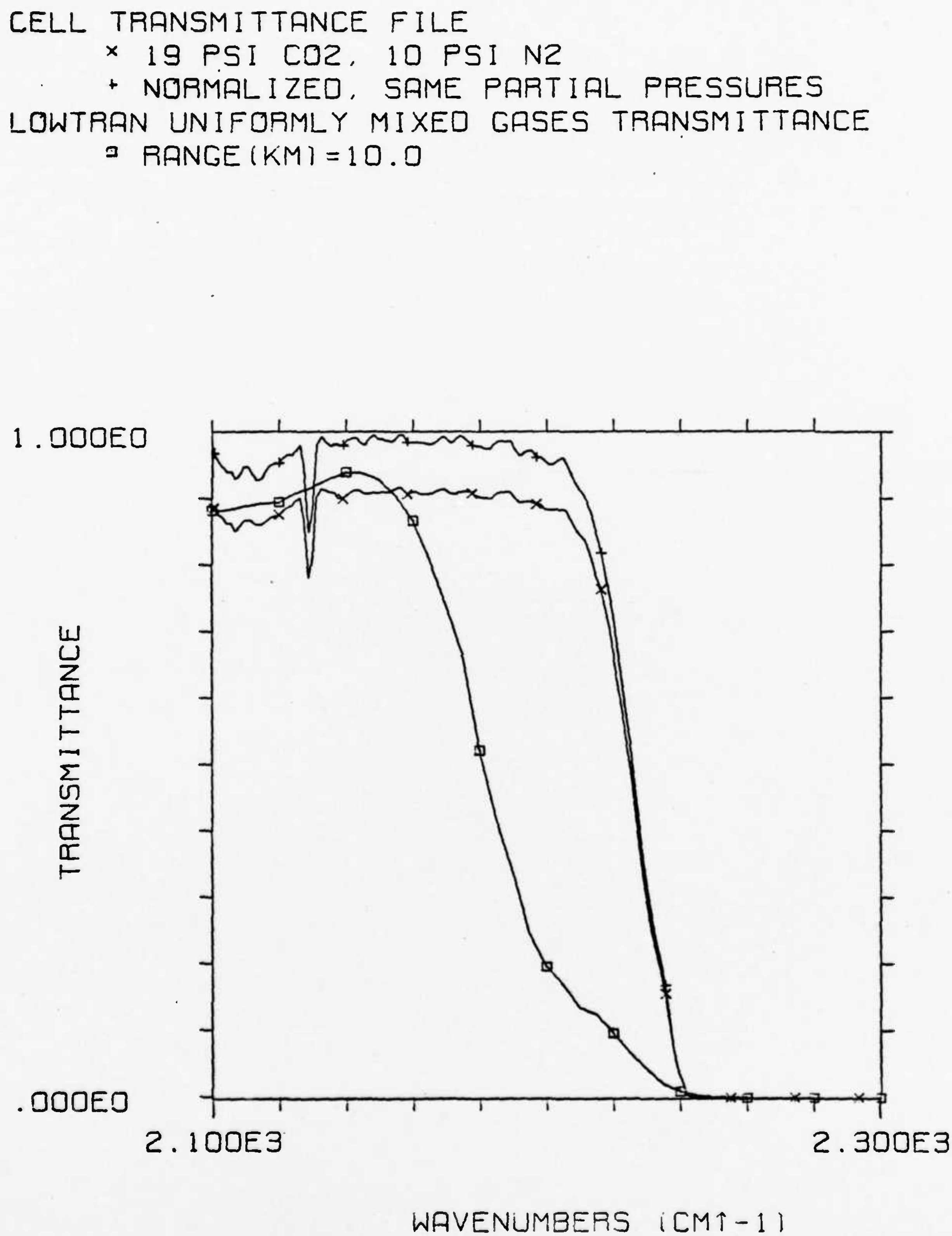

Figure 21. Comparison of Measurement 4 with LOWTRAN

figures as a baseline for range estimation, the partial pressures of carbon dioxide in measurements 7 and 1 - 4 will be used to approximate ranges of 1, 2, 3, 7, and 10 km. By multiplying each of these measurements by an Aggregate model calculation for nitrous oxide corresponding to the range estimation using a CO_2/N_2O ratio of 330/.028, the results can be compared to the LOWTRAN calculations. Figures 22 to 26 show this comparison. In each case the two cell measurements, original and normalized, are multiplied by a nitrous oxide calculation and plotted. The LOWTRAN calculations, total transmittance and carbon dioxide (uniformly mixed gases), show that the range estimations for the measurements give reasonable results. The total transmission from LOWTRAN is shown only to give a reference to atmospheric absorption and to show the effect of absorption by water vapor. Since water vapor cannot be added to the cell in high enough concentrations, only the carbon dioxide calculations from LOWTRAN can be used to characterize the cell measurements.

C. CELL ATMOSPHERES CONTAINING NITROUS OXIDE

Since the absorption by nitrous oxide has been determined to play an important role in shaping the weak line absorption region of carbon dioxide in the atmosphere, reliable pressure measurement procedures are required to make repeatable cell measurements. The ratio of carbon dioxide to nitrous oxide in the atmosphere is 1.2×10^4. Therefore, if a range of 2 km is to be simulated in the absorption cell with 4 PSI of carbon dioxide, only 3.4×10^4 PSI of nitrous oxide is required. Since a pressure this small cannot be measured with the equipment in the laboratory, a small volume was filled with nitrous oxide to pressures measurable using the gas cylinder regulator and then the gas was expanded into the cell. Using engineering drawings, the volume of the cell was calculated as 4.437×10^3 in^3. The small volume external to

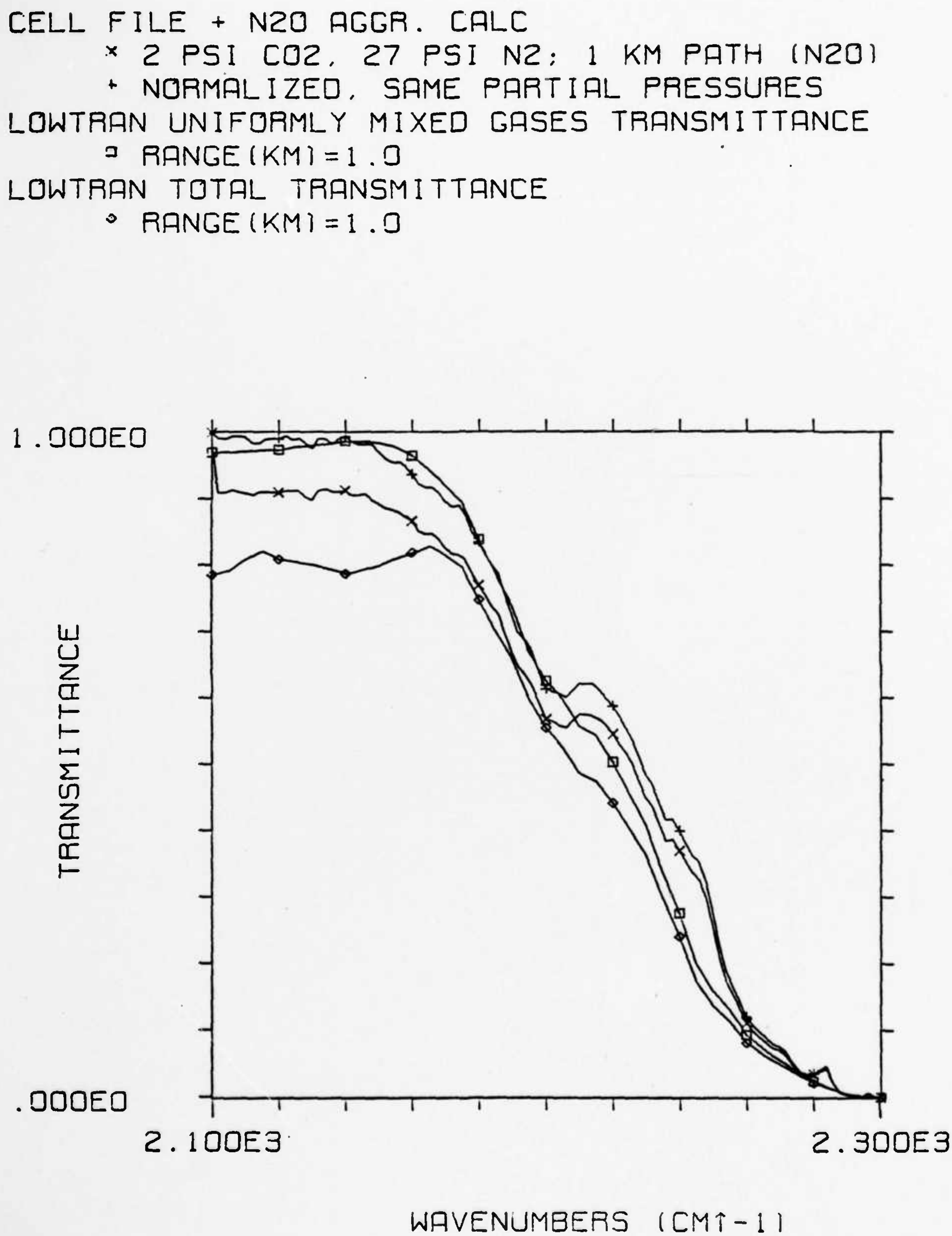

Figure 22. Comparison of Measurement 7 and Aggregate Model with LOWTRAN

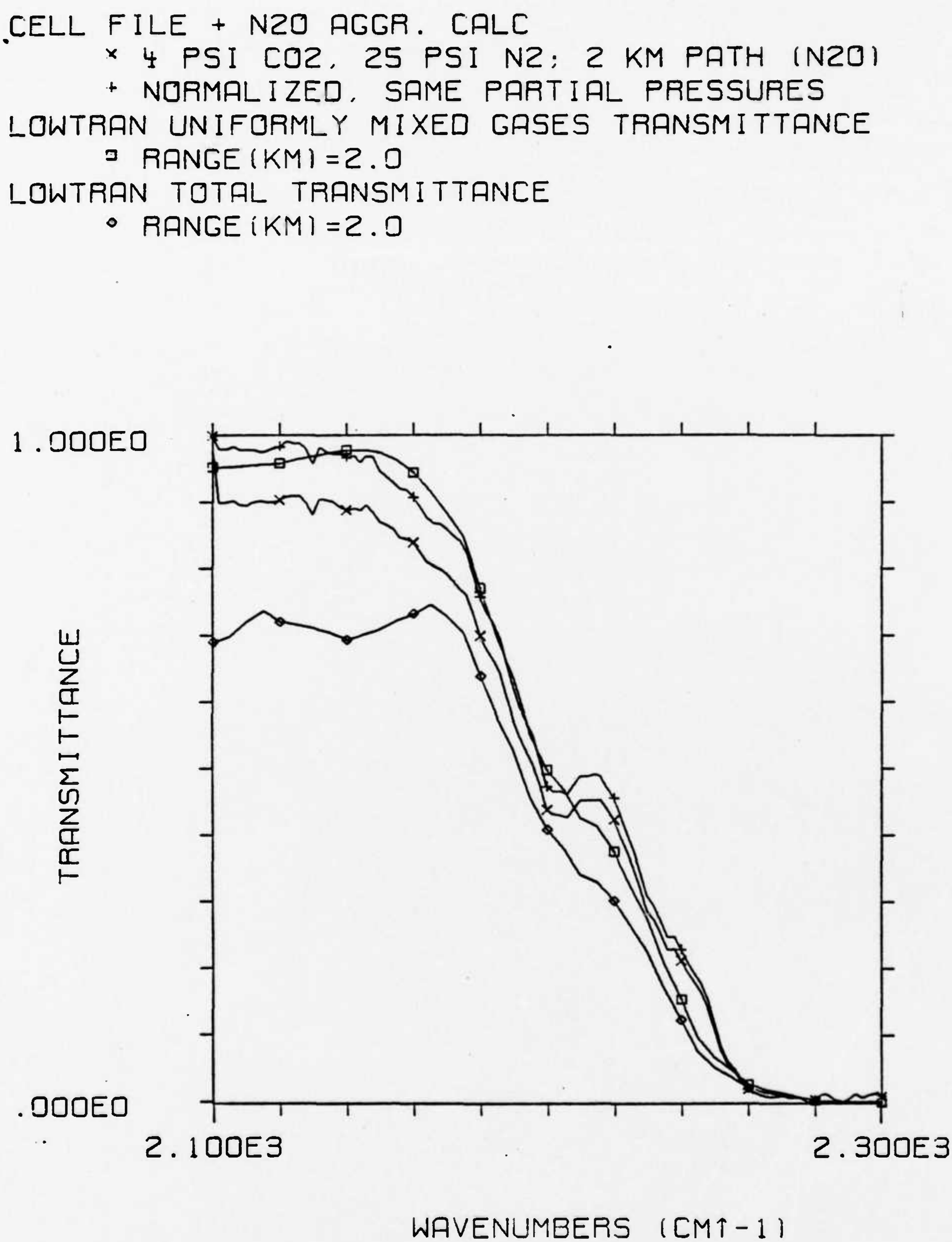

Figure 23. Comparison of Measurement 1 and Aggregate Model with LOWTRAN

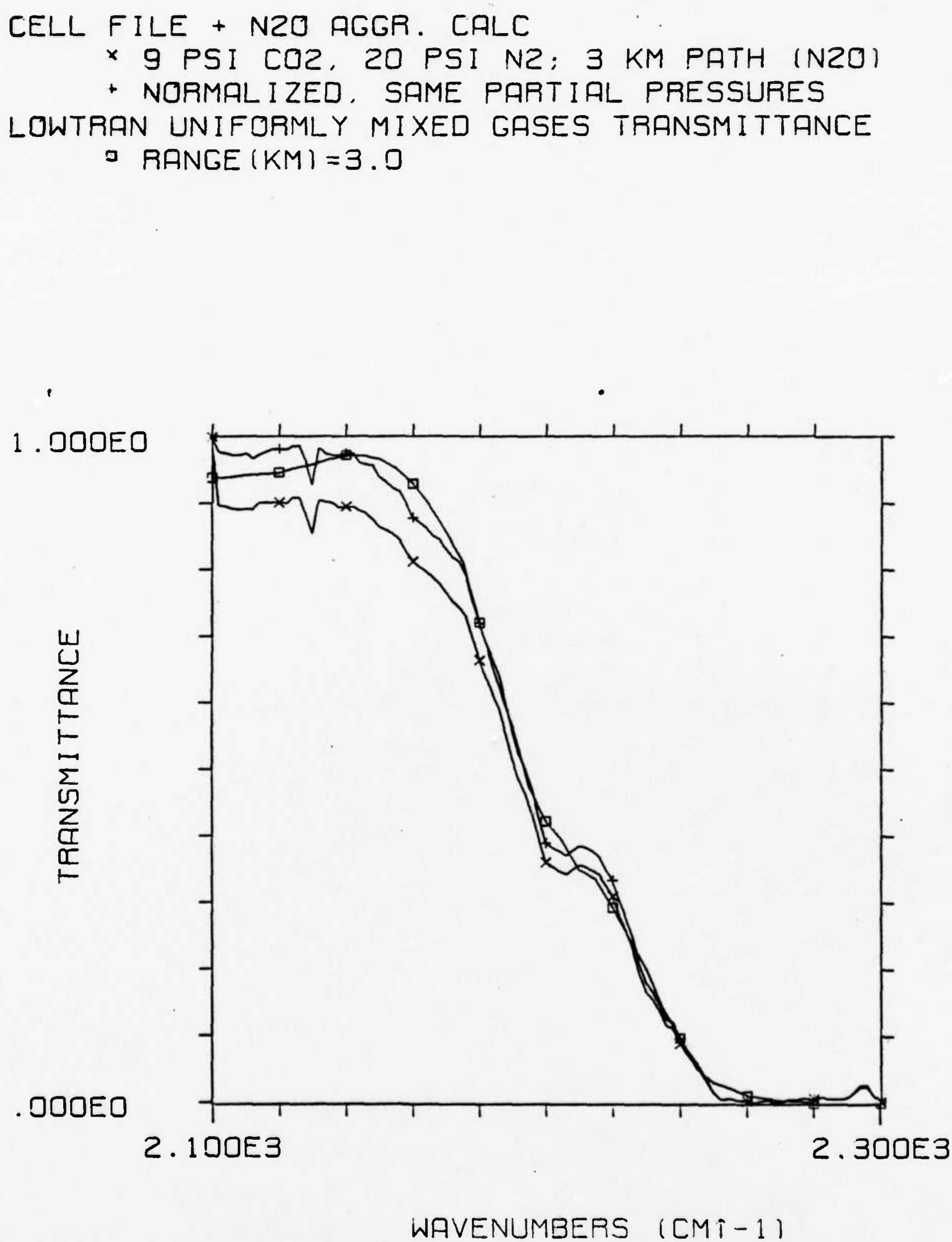

Figure 24. Comparison of Measurement 2 and Aggregate Model with LOWTRAN

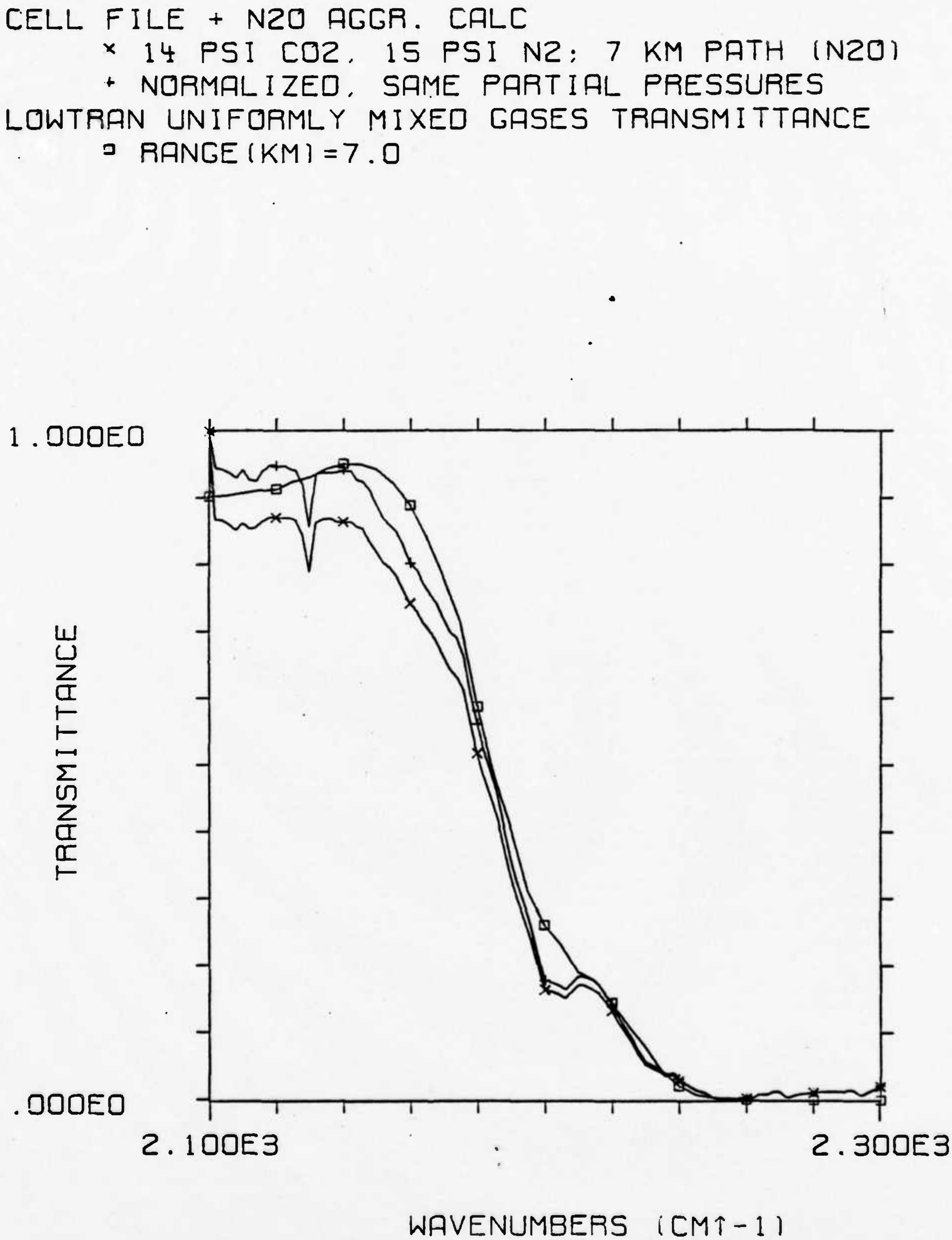

Figure 25. Comparison of Measurement 3 and Aggregate Model with LOWTRAN

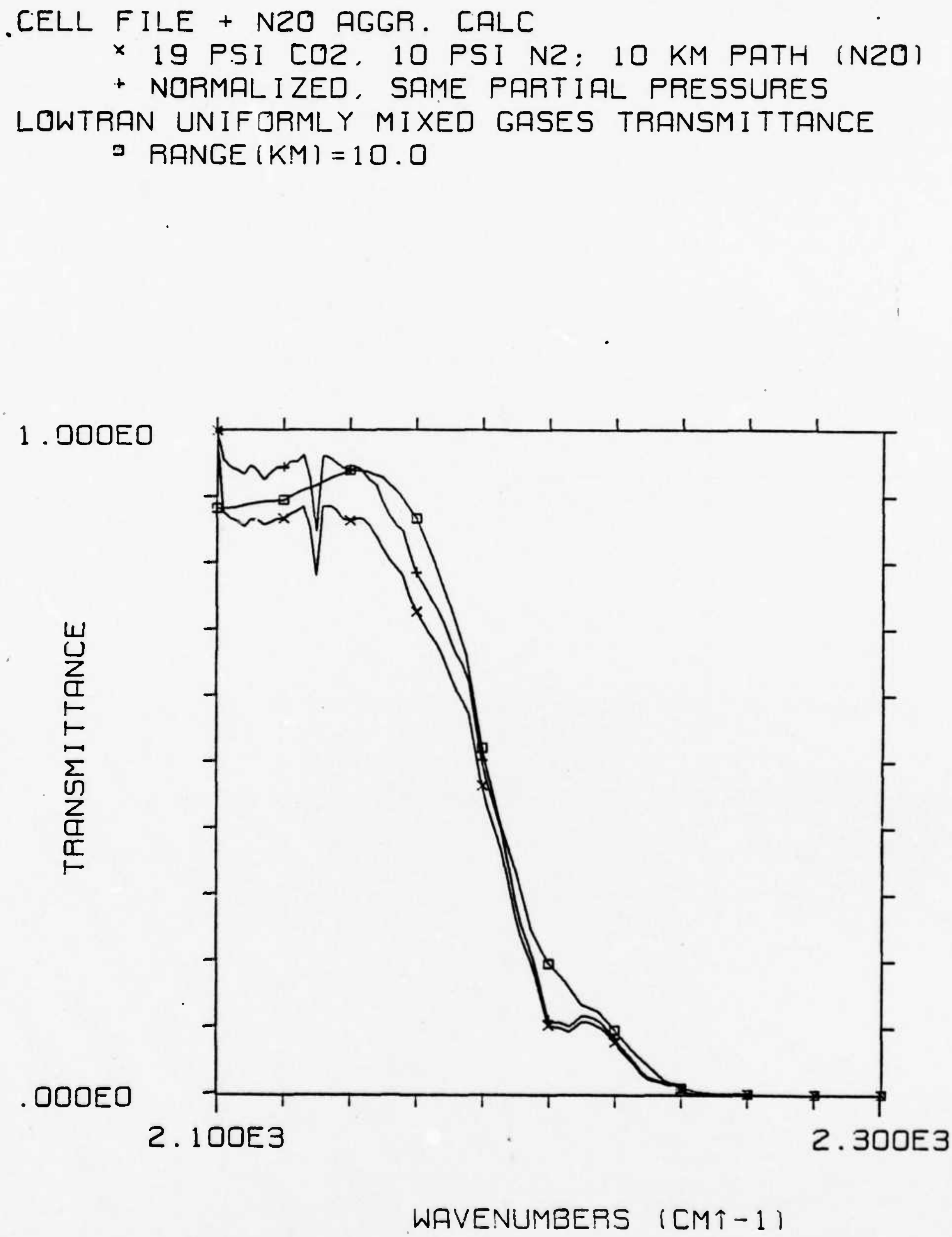

Figure 26. Comparison of Measurement 4 and Aggregate Model with LOWTRAN

the cell was fabricated from a short piece of 1/4 inch copper tubing with valves at each end. The volume of the cell divided by the ratio 1.2×10^4 gives a volume of .38 in^3 required for the copper tubing. The 1/4 inch tubing length, inside diameter of .22 inches, therefore must be 7.66 inches in length to achieve this volume. Since we wanted to measure the pressure using the gas regulator, which has a pressure range of 4 - 60 PSI, a length of 8 inches was chosen for the copper tubing. Using this length of tubing, the ratio of the cell volume to the tubing volume was calculated to be 1.4×10^4.

Using the Aggregate model calculations for nitrous oxide at 2235 cm^{-1}, the range as a function of transmittance was determined by using least square techniques for fitting a straight line to equations of the form, $\ln R = \ln A + B\,T$. The correlation coefficient of the least square fit using the calculations in Table II is .99. The range as a function of transmittance is given by:

$$R = 15.18 \, \mathrm{EXP}\,(-5.13\,T) \qquad (2)$$

where

R = range in km

T = transmittance

Measurements 20-24 give values of .7167, .1181, .6229, .4644, and .2246 for the transmittance of nitrous oxide at 2235 cm^{-1}. A comparison of these values for the transmittance versus the range can now be made. Figure 27 shows the pressure of nitrous oxide in the tubing versus the range.

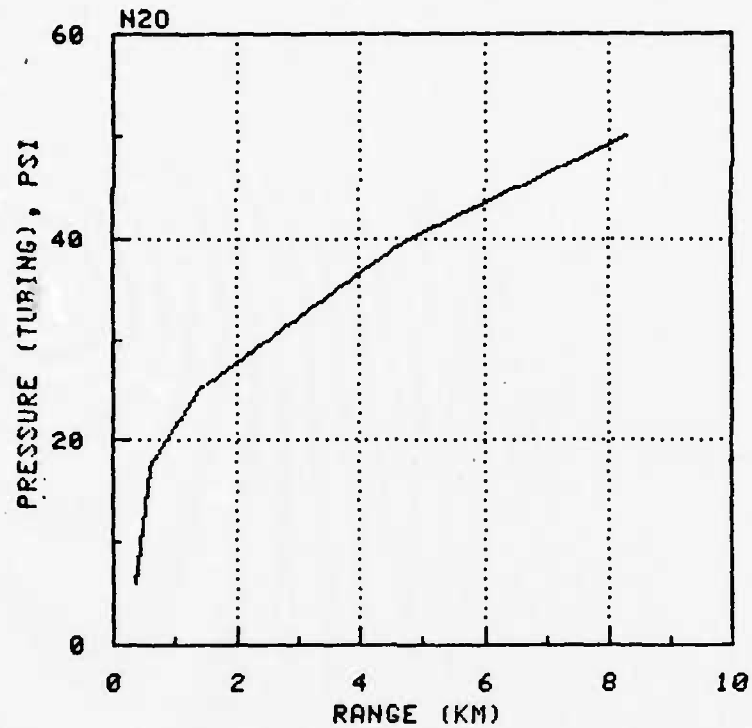

Figure 27. Nitrous Oxide Pressure vs. Range

Measurements 25-28, shown in Figures 28 to 30, used Figure 27 to determine the partial pressure of nitrous oxide in the cell. The partial pressures of carbon dioxide were determined by comparing the strong line absorption band of previous measurements with LOWTRAN as before. These measurements correspond to the LOWTRAN calculations fairly well. Table V lists the values of the range and partial pressures of nitrous oxide in the tubing and of carbon dioxide in the cell.

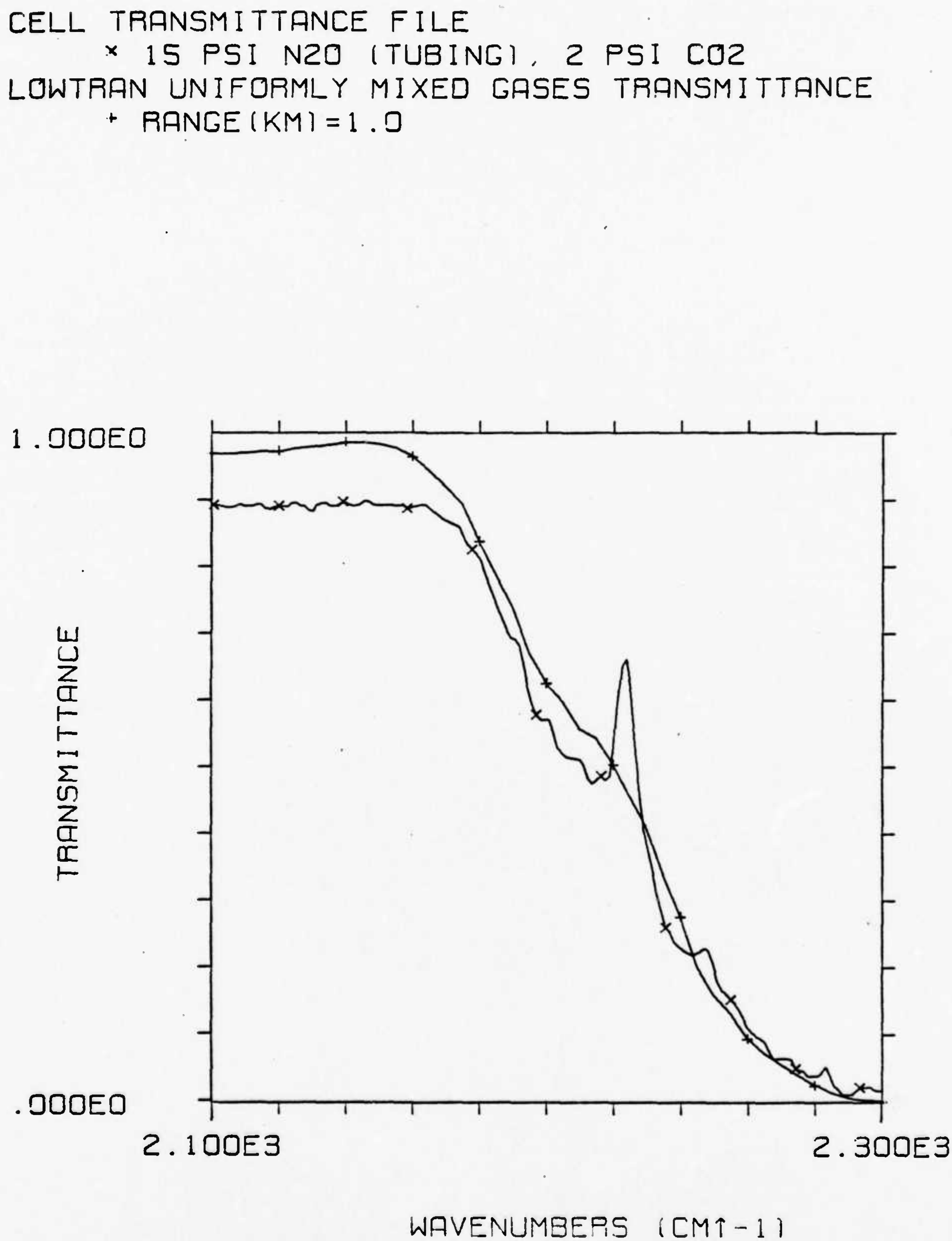

Figure 28. Comparison of Measurement 25 with LOWTRAN

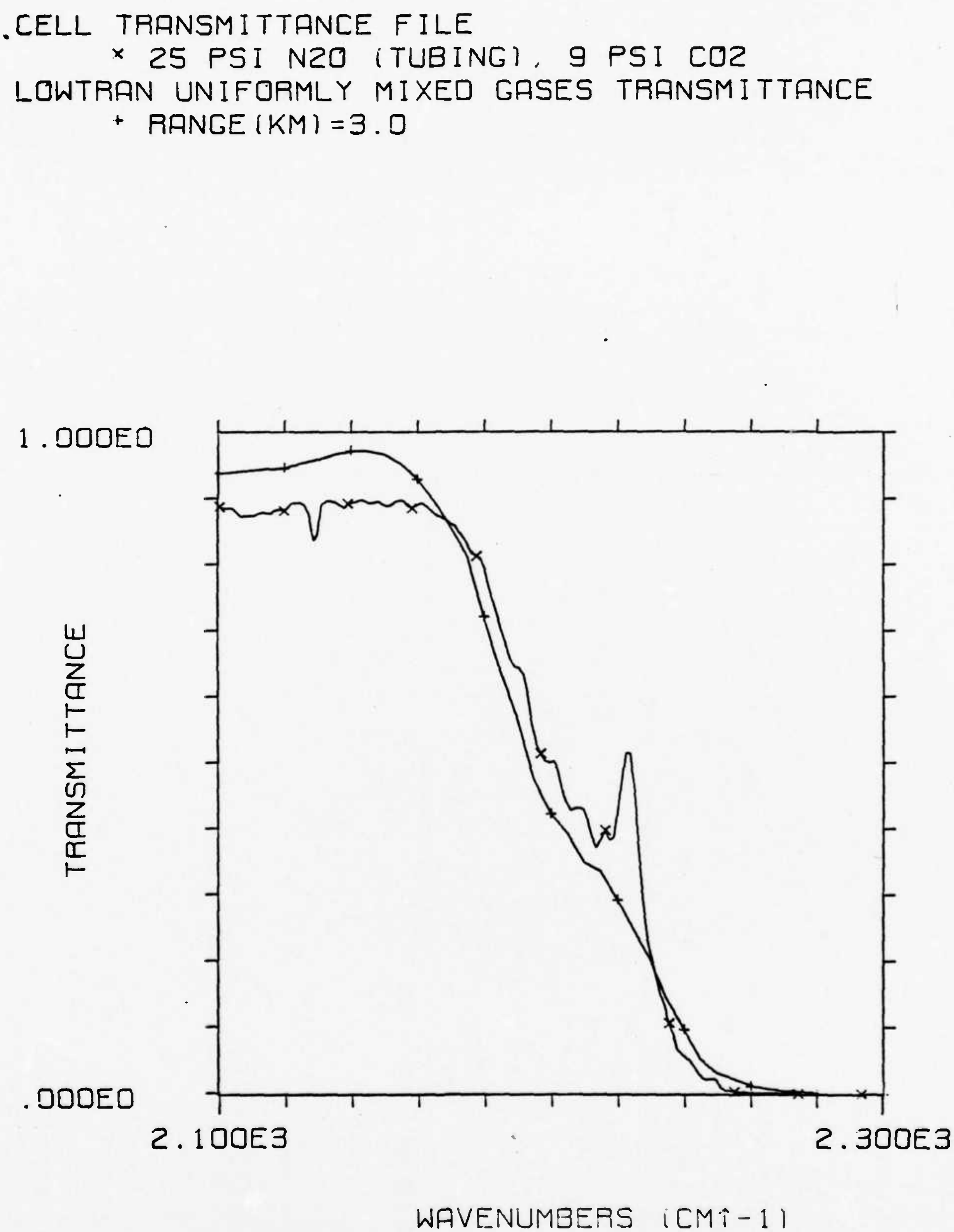

Figure 29. Comparison of Measurement 26 with LOWTRAN

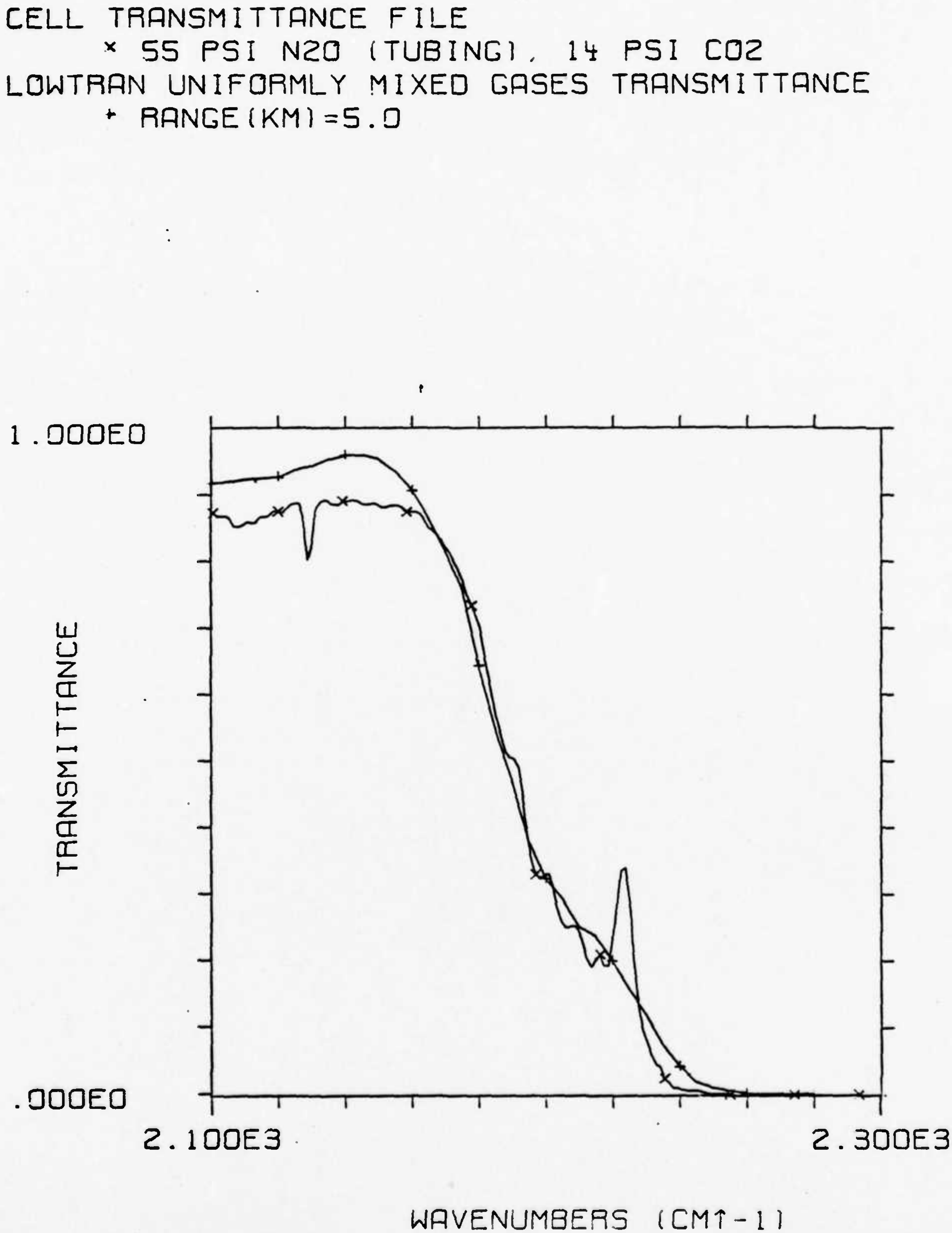

Figure 30. Comparison of Measurement 27 with LOWTRAN

TABLE V. RANGE CALIBRATION

RANGE (km)	N_2O (TUBING), PSI	CO_2 (CELL), PSI
1	15	2
3	30	9
5	40	14
7	55	19

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

The atmospheric absorption cell developed by the Avionics Laboratory has been characterized by transmittance measurements through the cell using a spectrometer and comparing the measurements with atmospheric transmittance models. The cell is limited to simulating horizontal paths of no longer than 8 - 10 km. Path lengths of less than 1 km are possible, but the gas mixtures in the cell are not reproducible due to the accuracy of the gas-handling equipment. The most important absorber in the 4 - 4.5 micron region for simulating atmospheric absorption is carbon dioxide. Carbon dioxide absorption is complete in the 2245 - 2390 cm^{-1} region. For frequencies less than 2245 cm^{-1}, the small quantities of nitrous oxide in the atmosphere are important in determining the spectral shape. The partial pressures of nitrous oxide and carbon dioxide listed in Table V give reasonable values for simulating ranges from 1 to 7 km. Furthermore, other partial pressures for nitrous oxide can be determined from Figure 27 to simulate ranges not listed in Table V.

The absorption cell developed by the Avionics Laboratory can be improved by replacing the pressure gauges of the gas-handling system with a more accurate system of gas measurement and by modifying the optical system so that the mirror mounts are isolated from the cell baseplate.

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APPENDIX

FIGURES OF CELL MEASUREMENTS

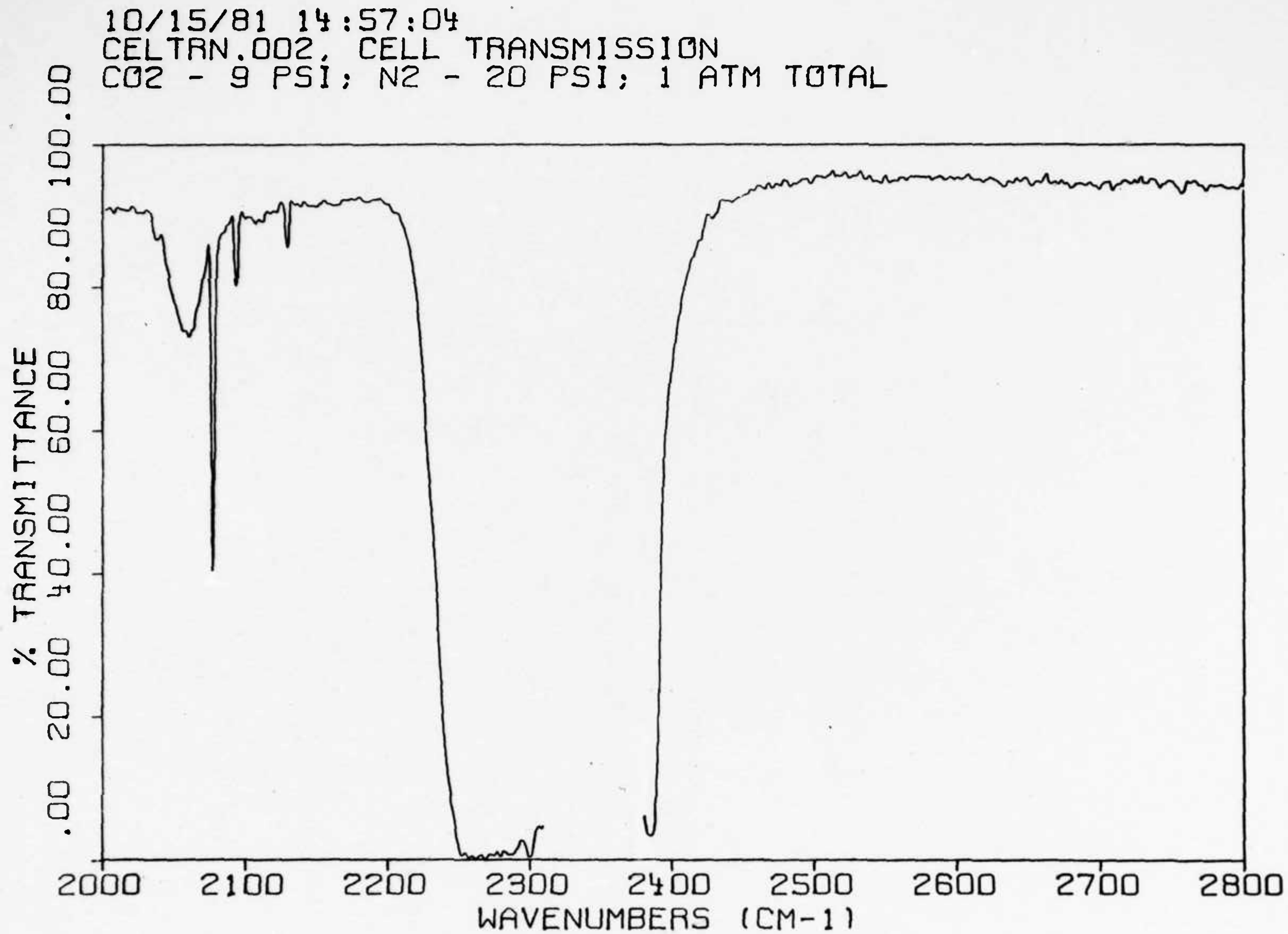


Figure A1. Measurement Number 2

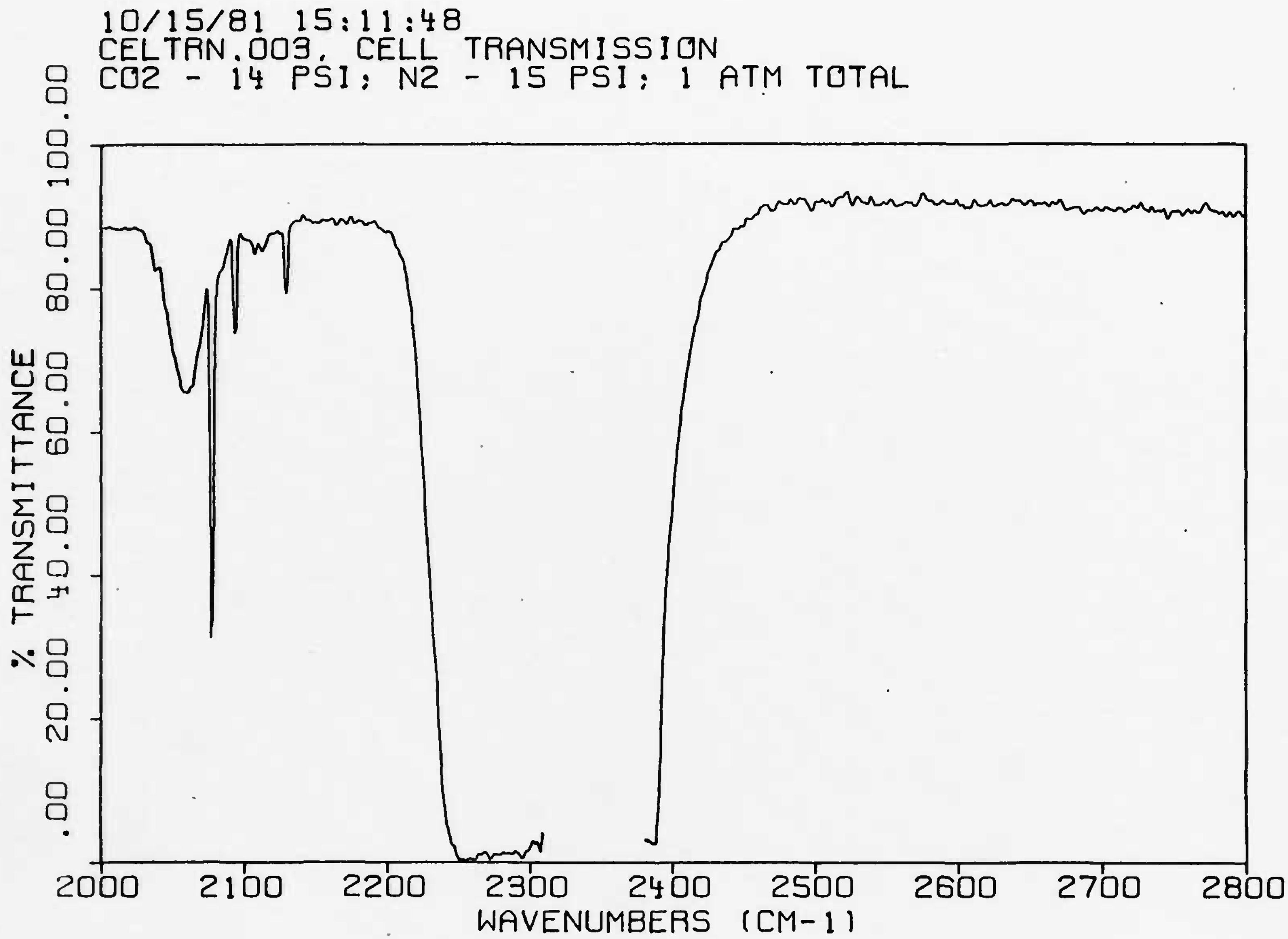


Figure A2. Measurement Number 3

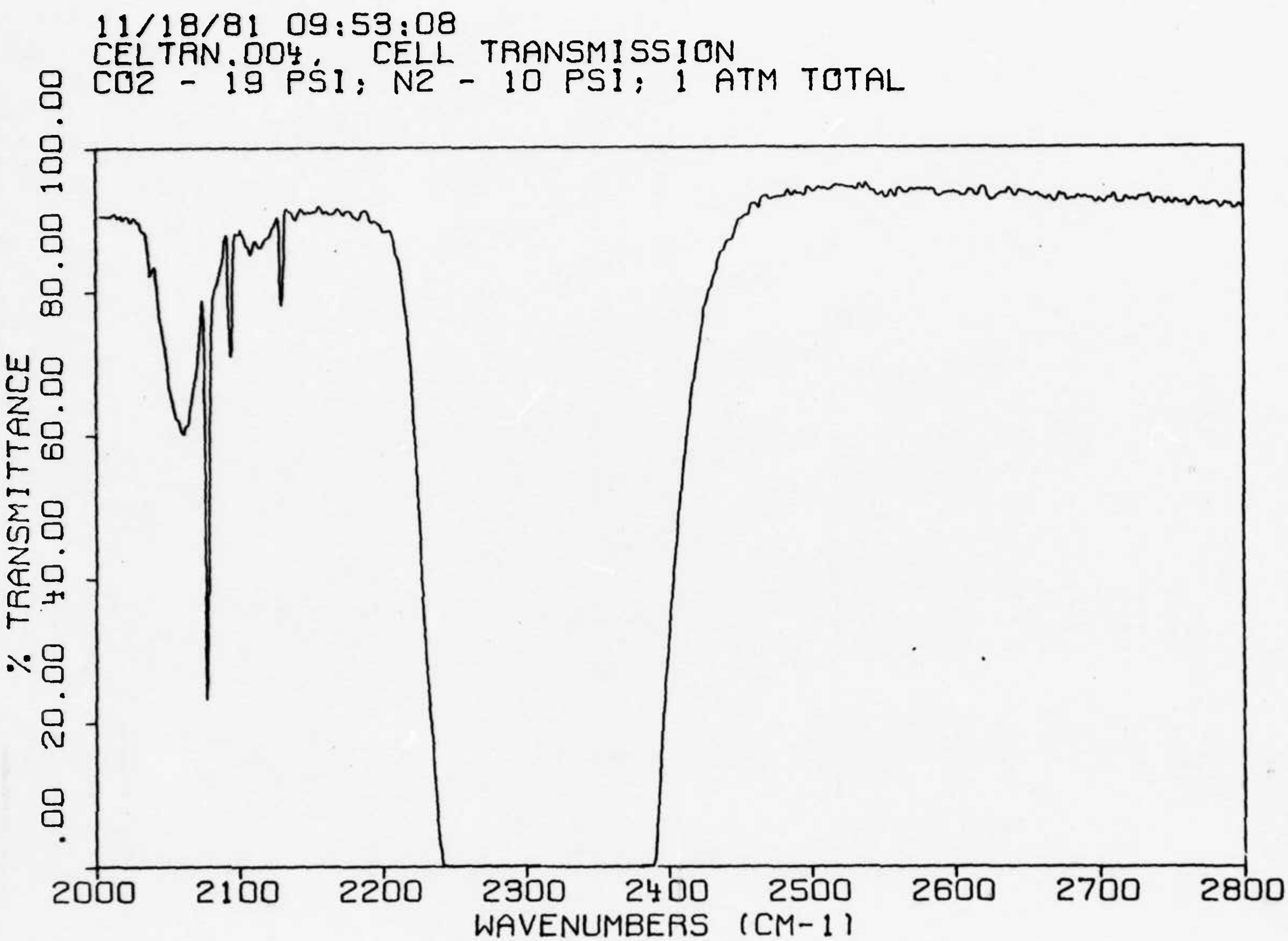


Figure A3. Measurement Number 4

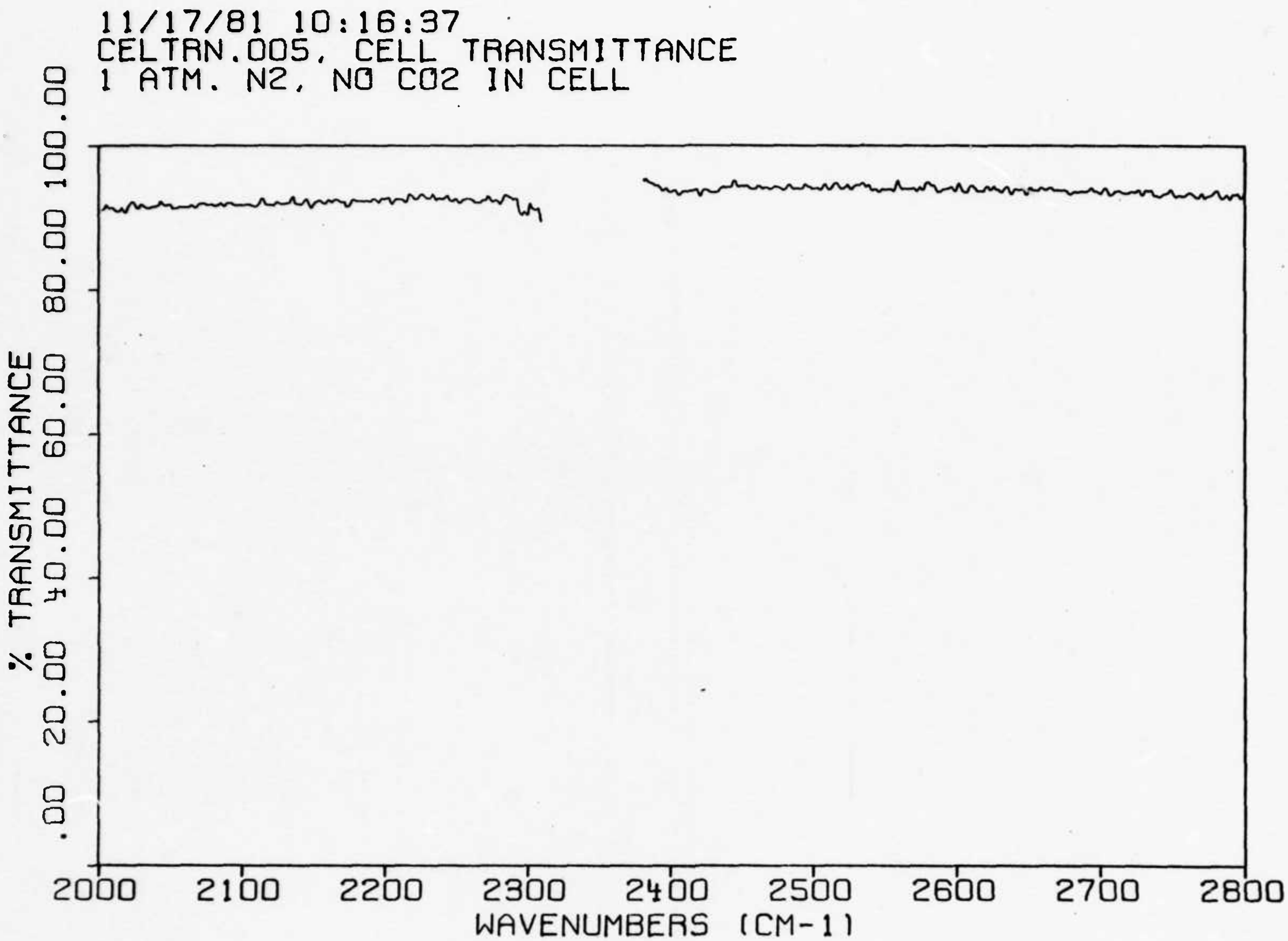


Figure A4. Measurement Number 5

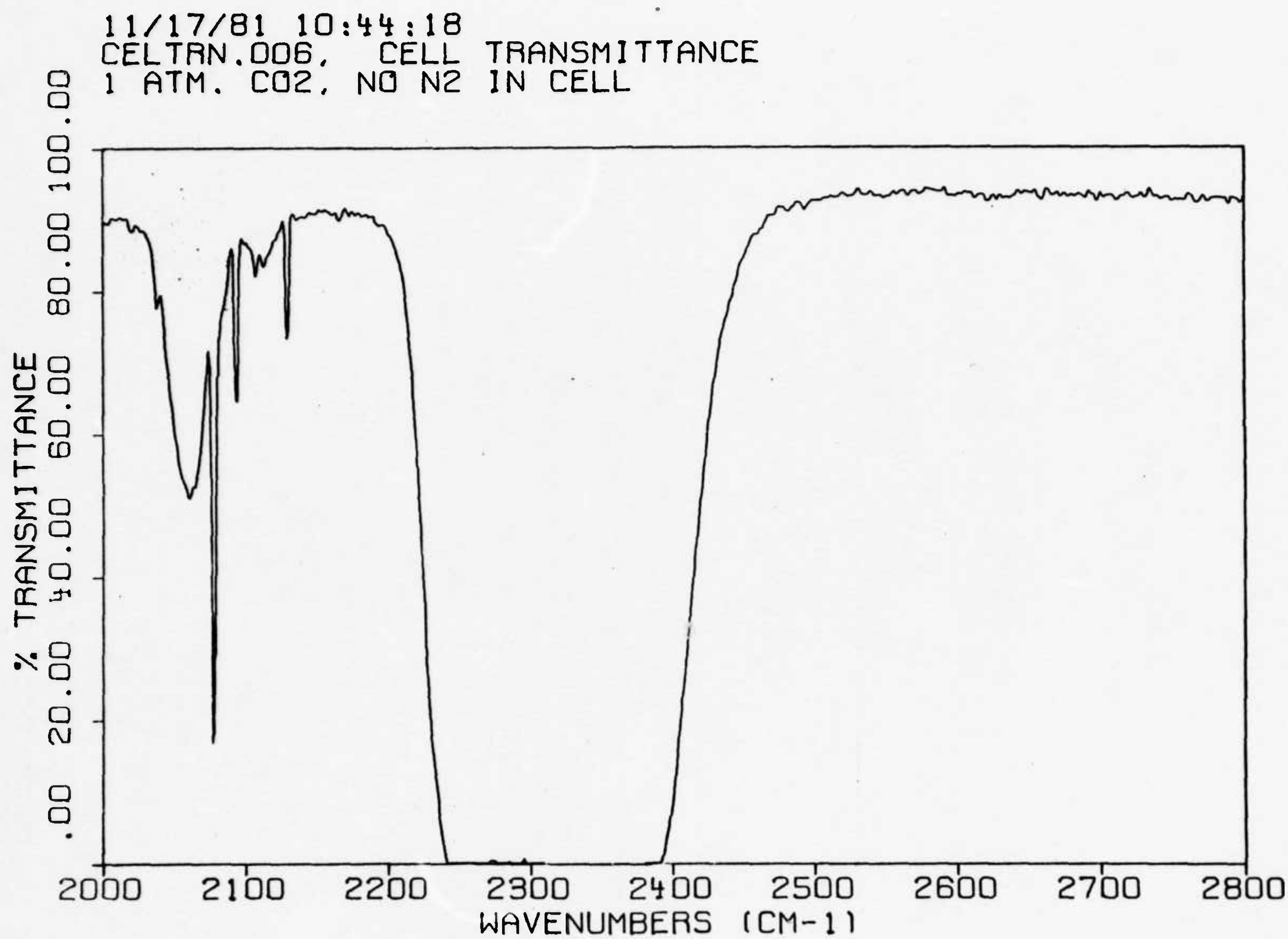
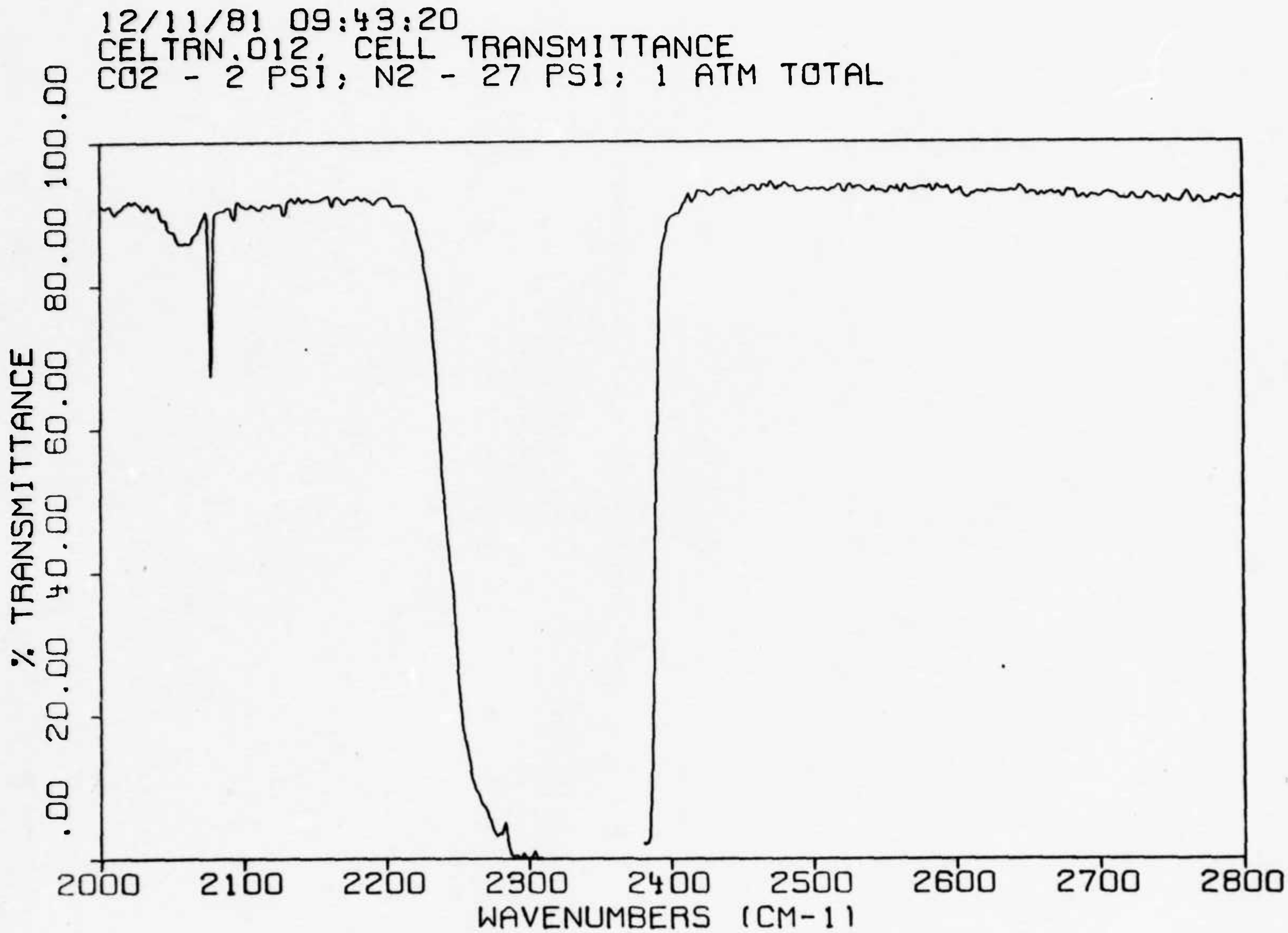


Figure A5. Measurement Number 6



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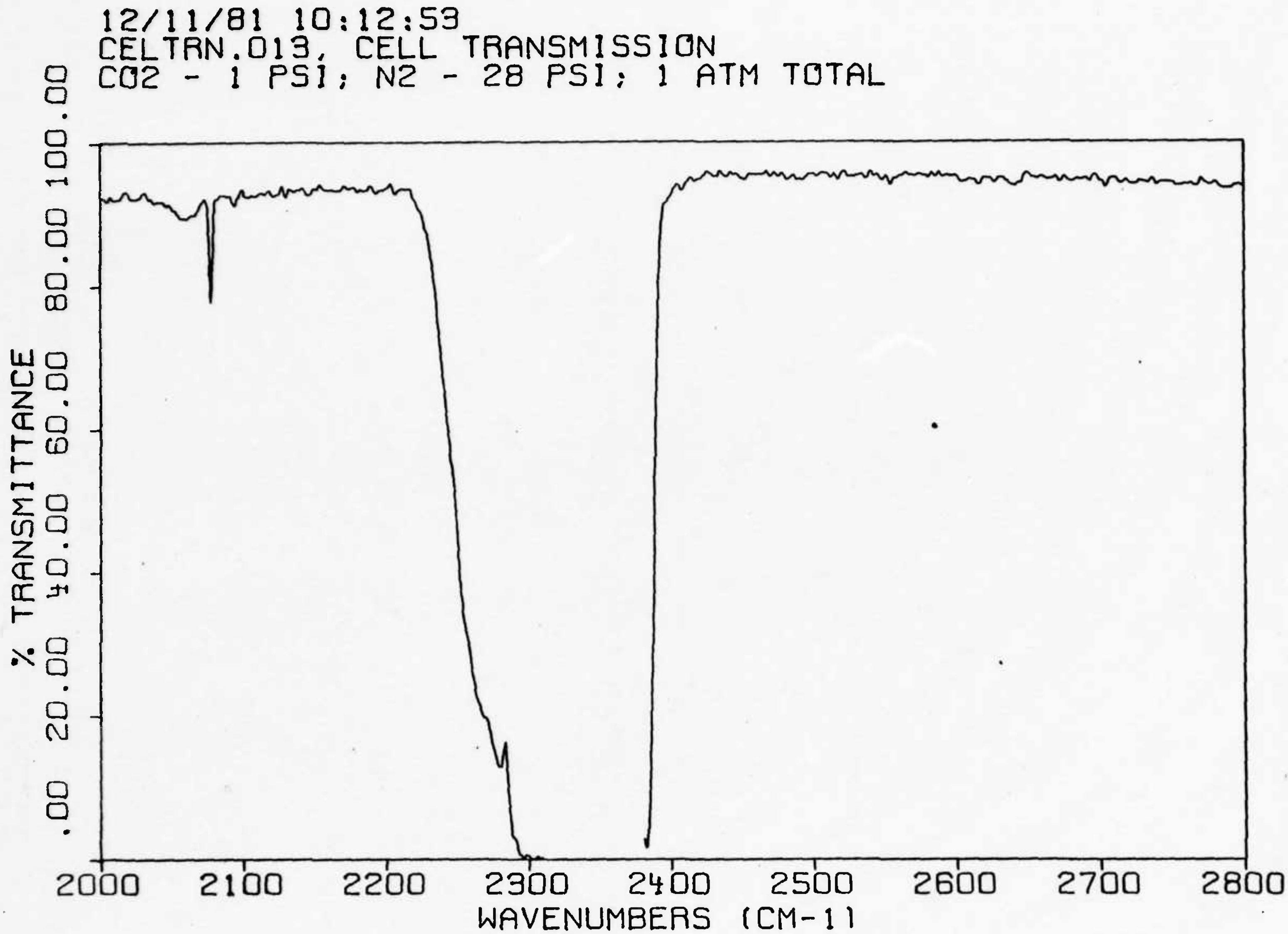

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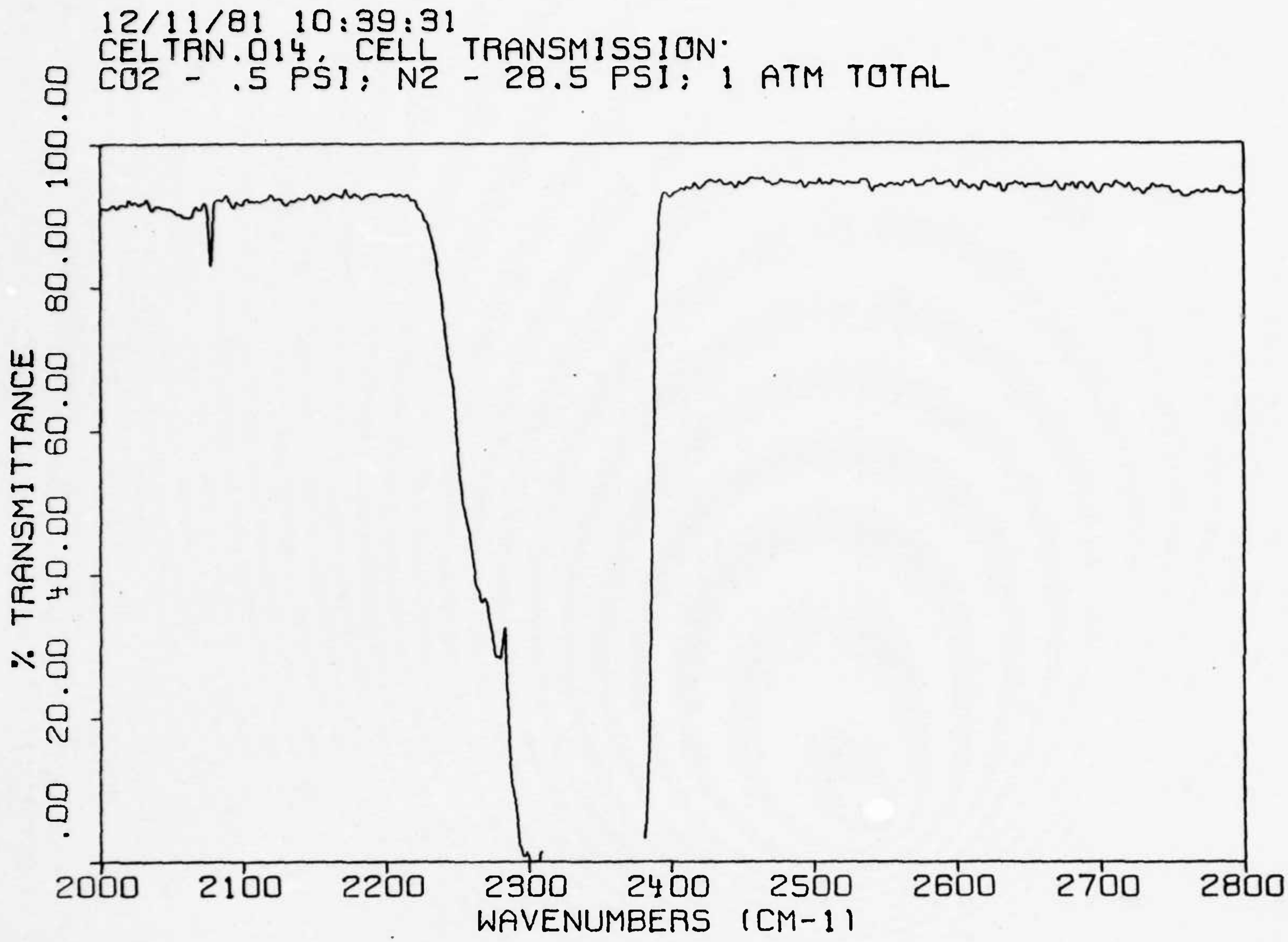

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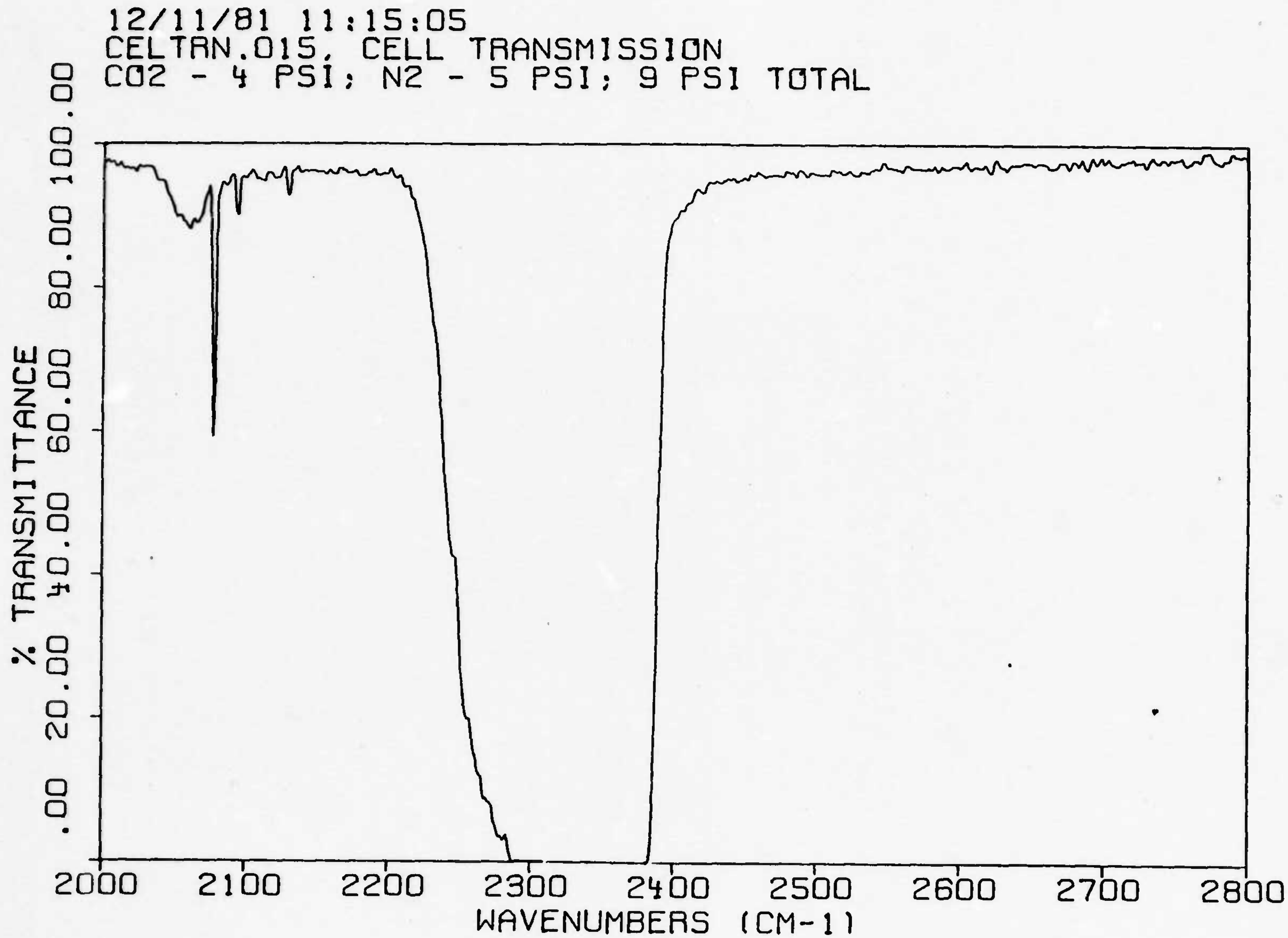

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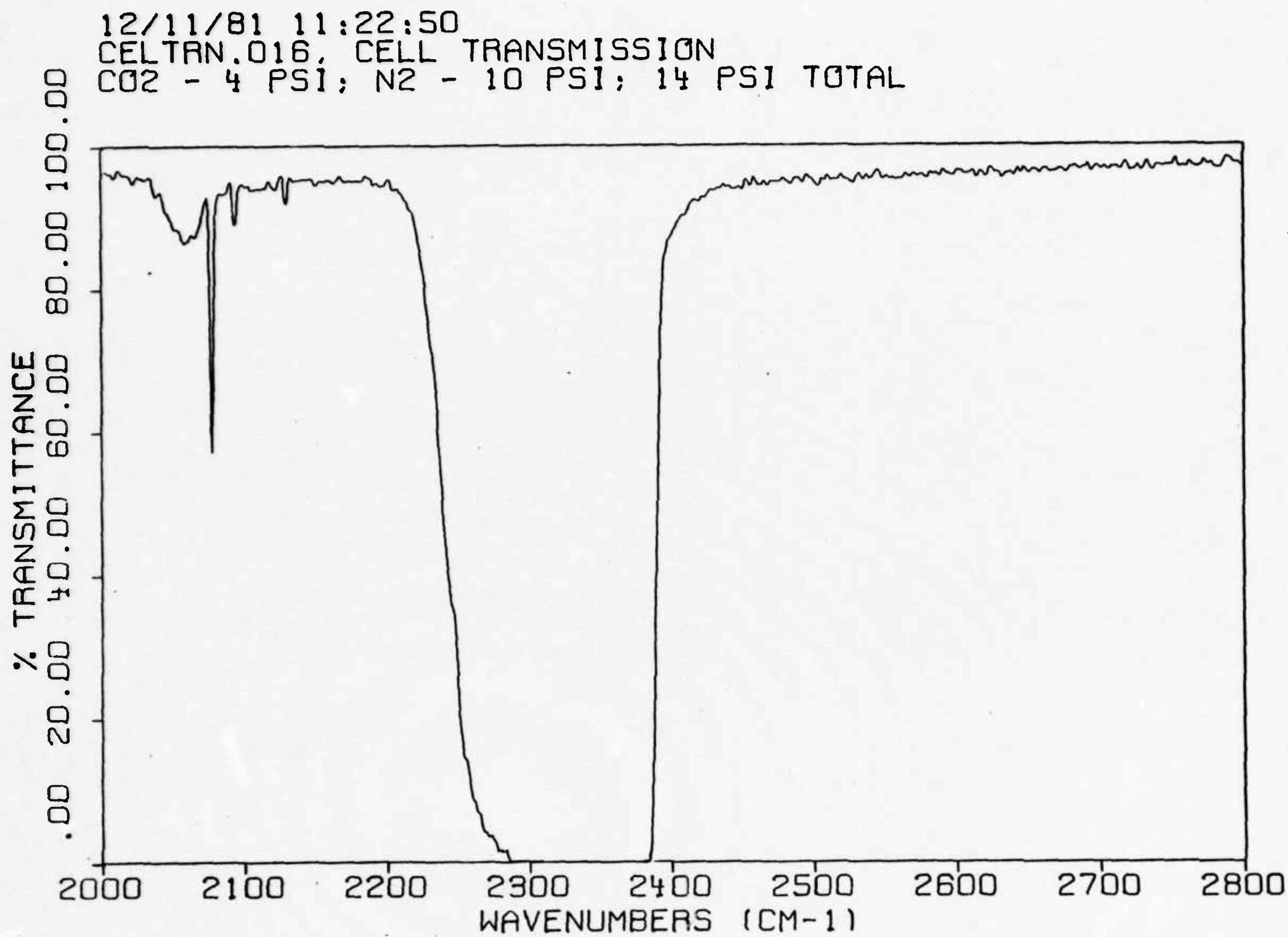
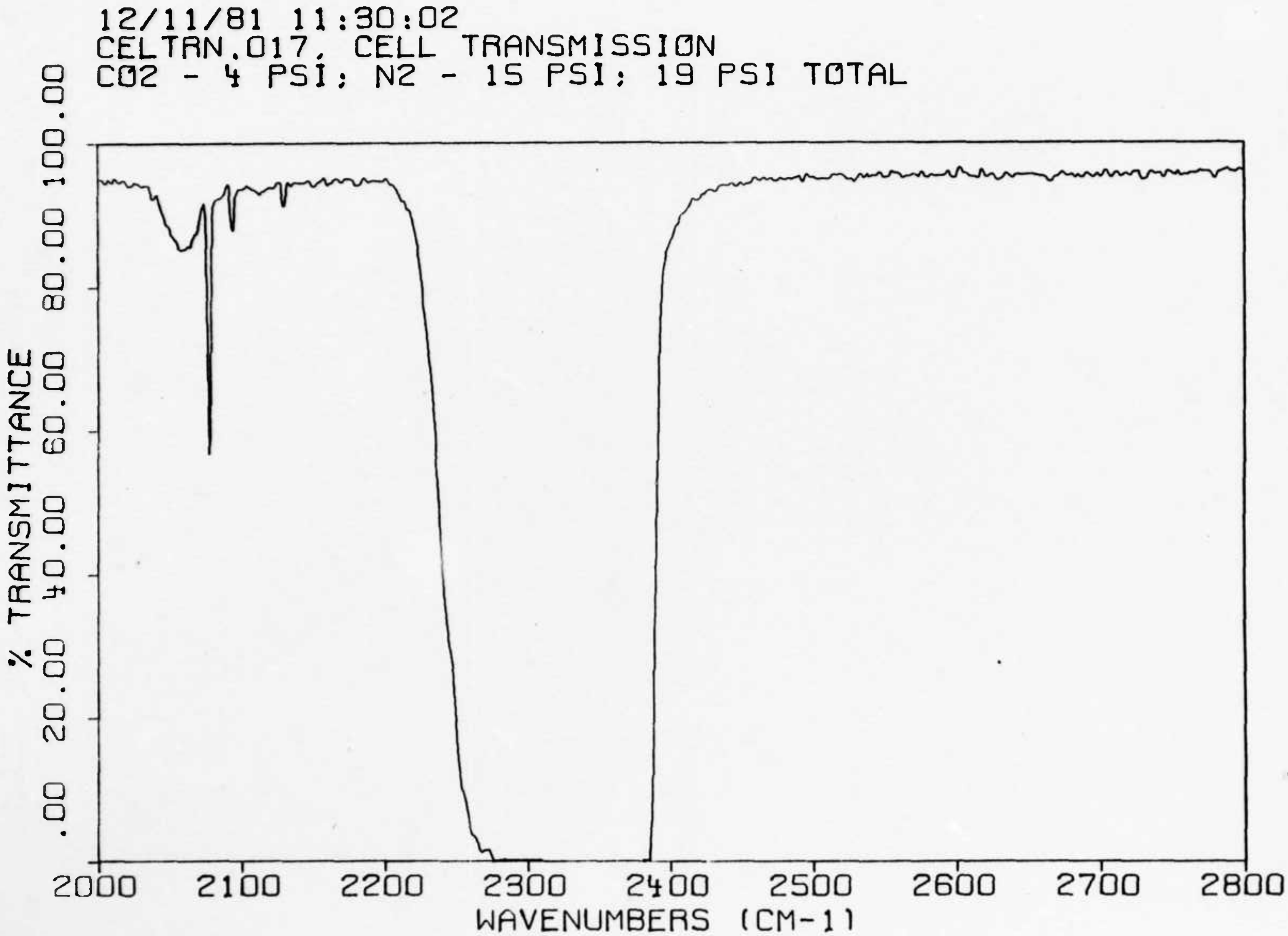


Figure A10. .easurement Number 11



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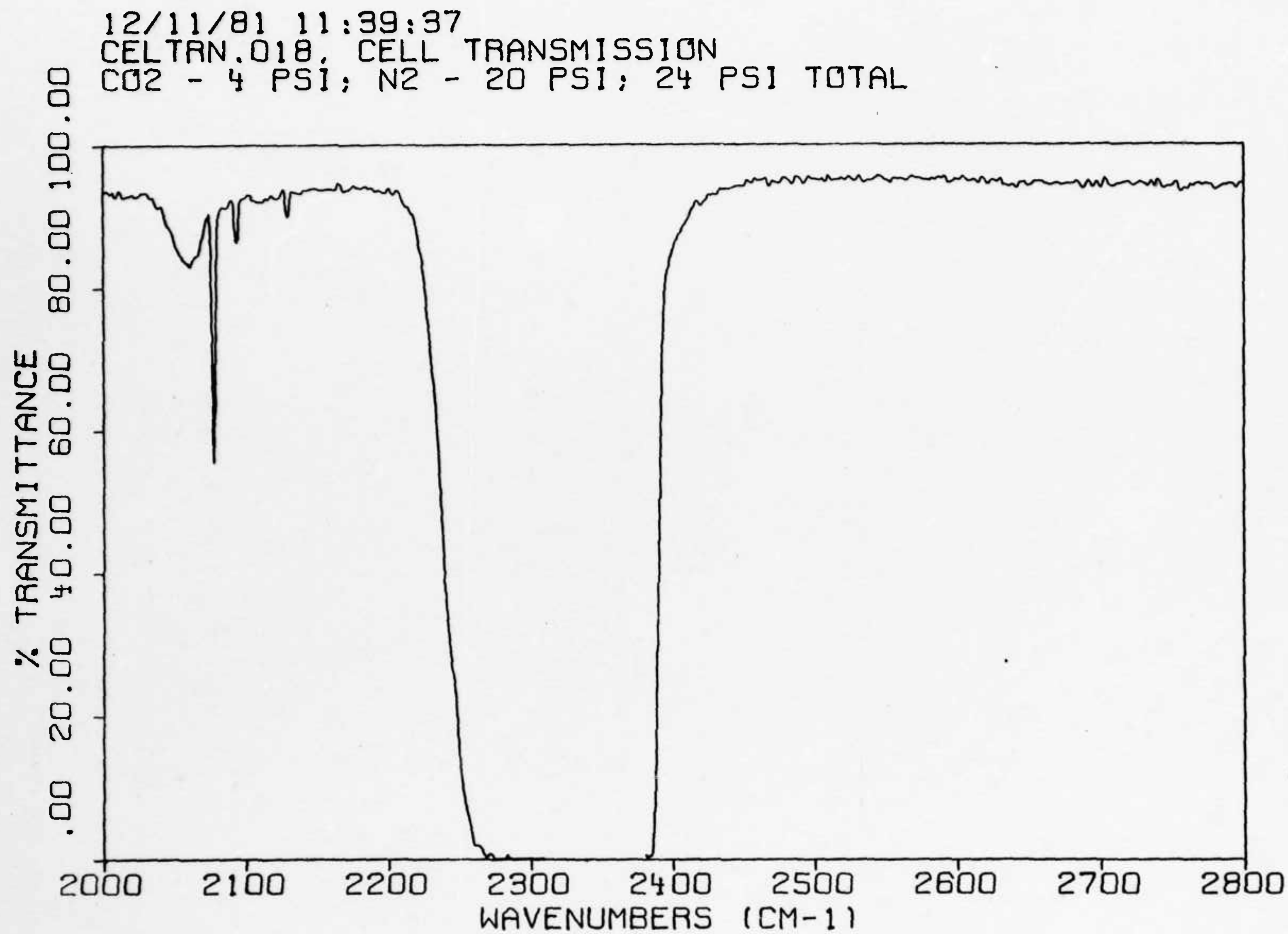

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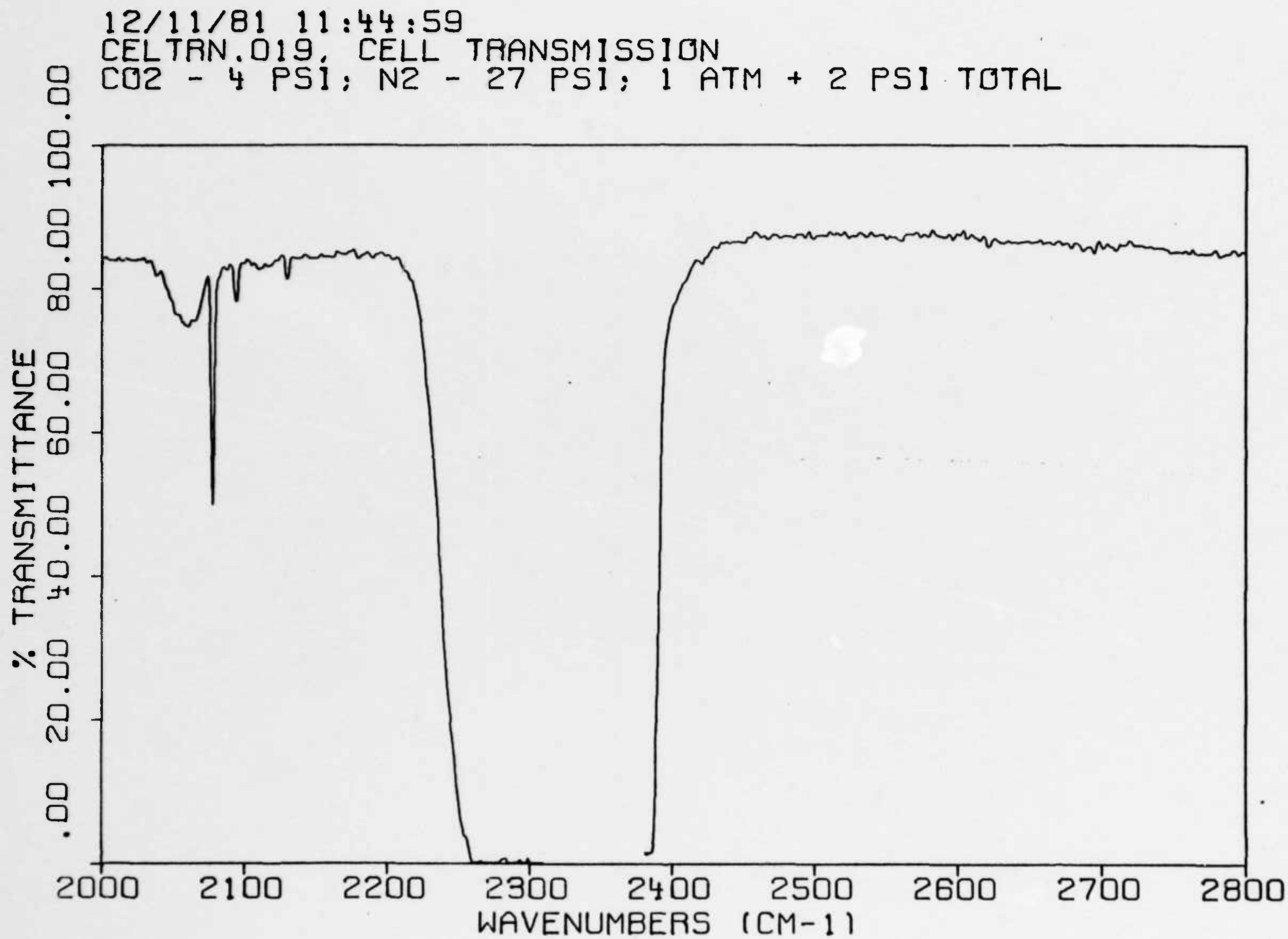

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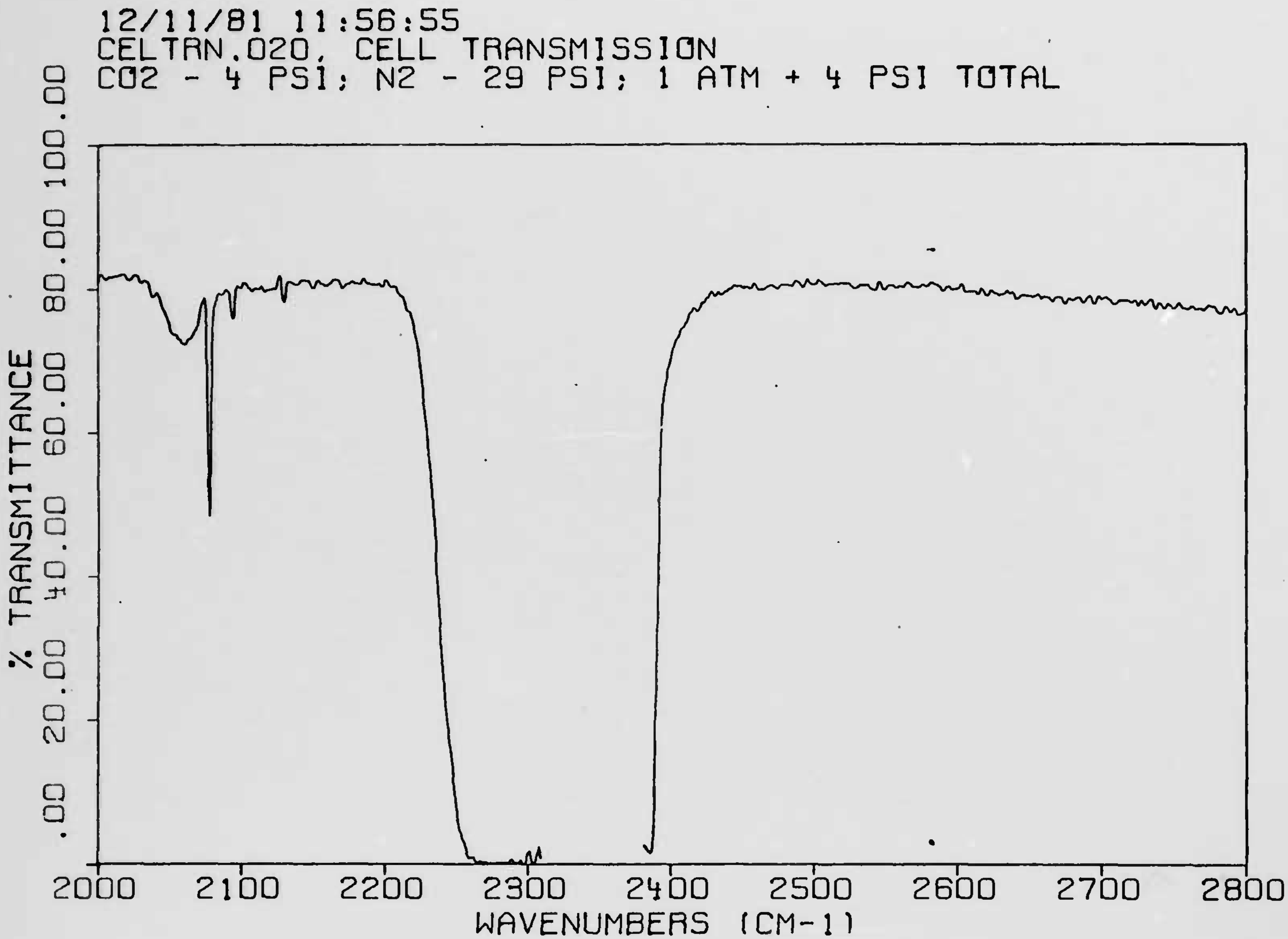

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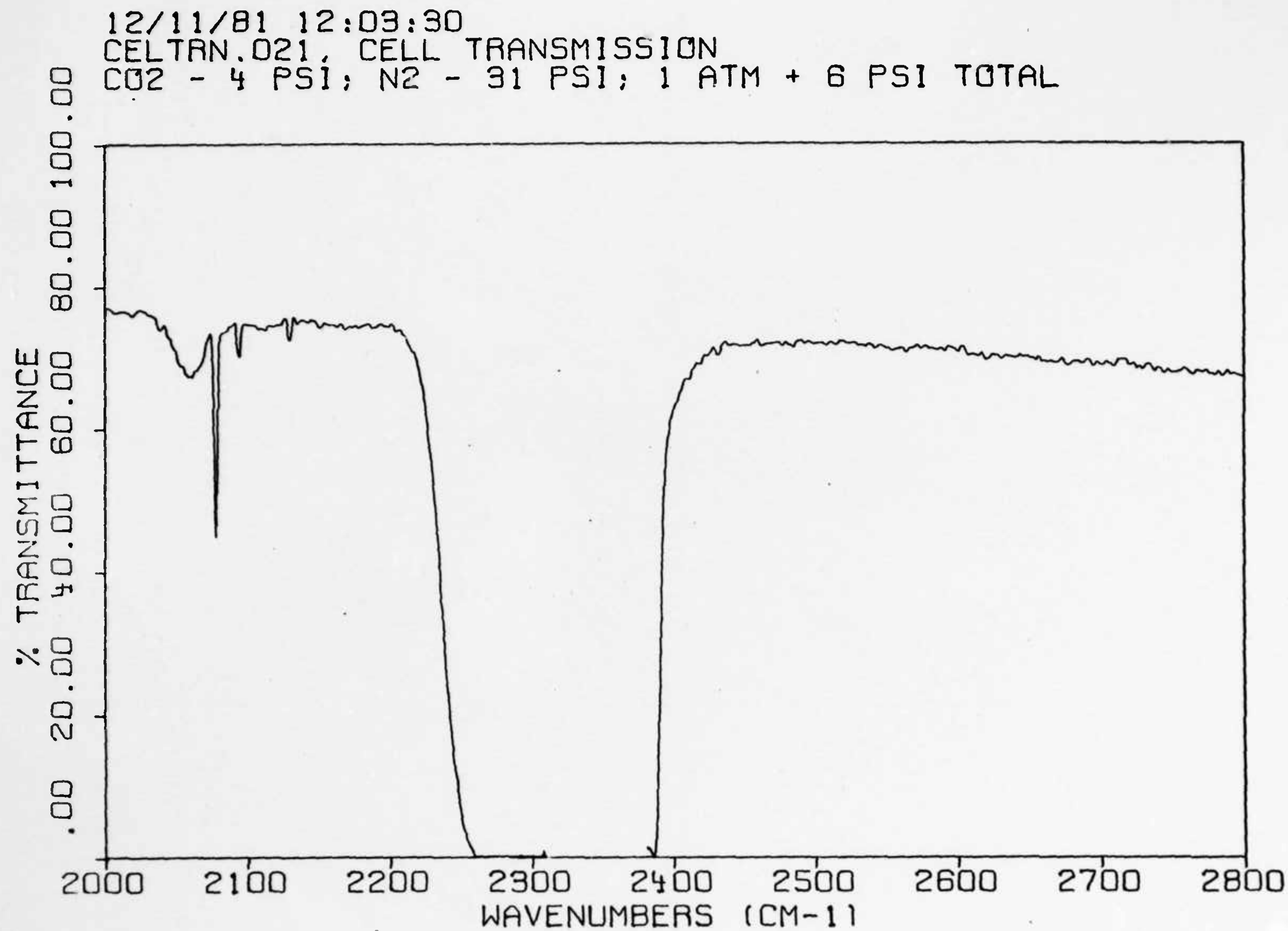

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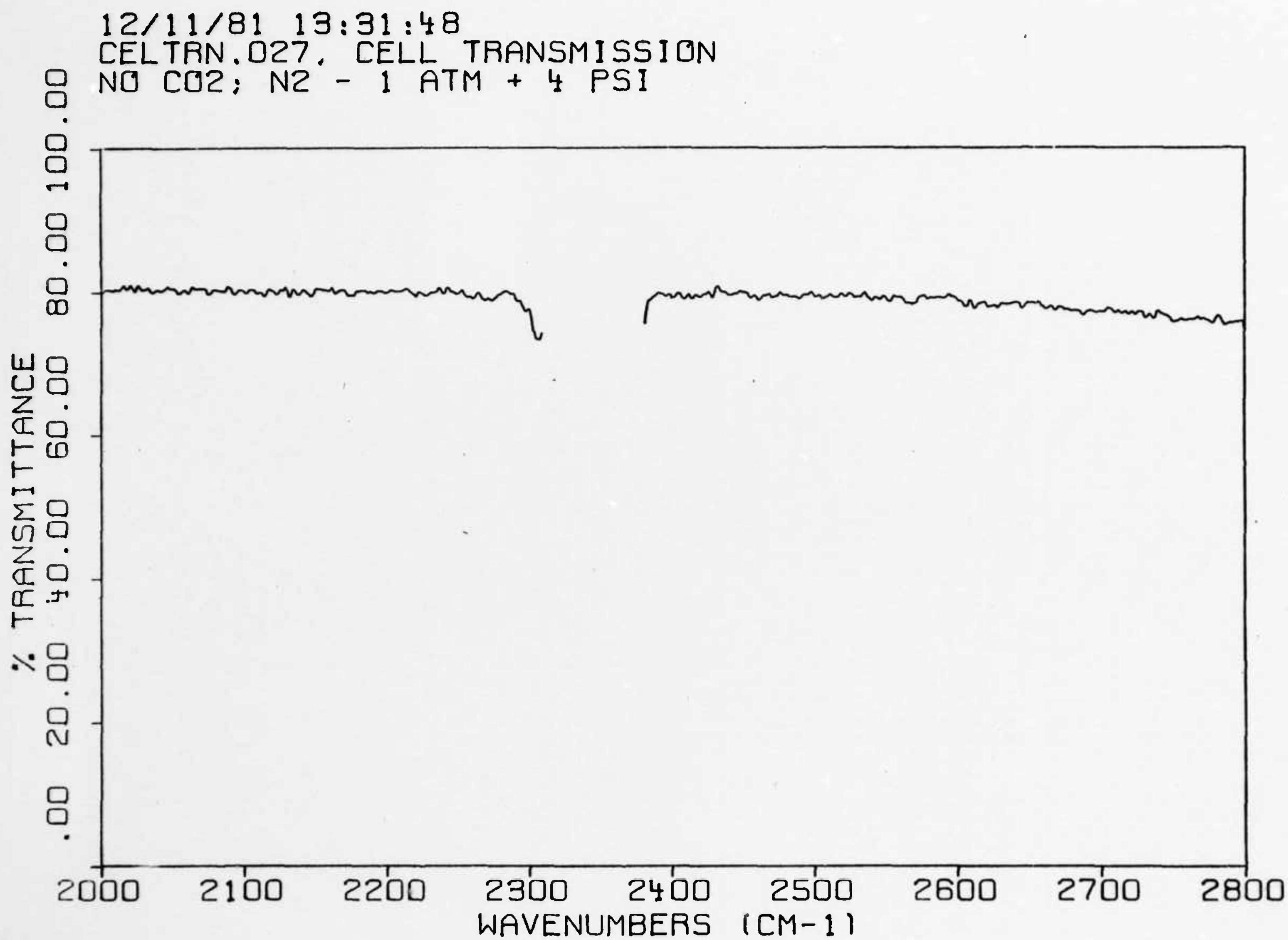
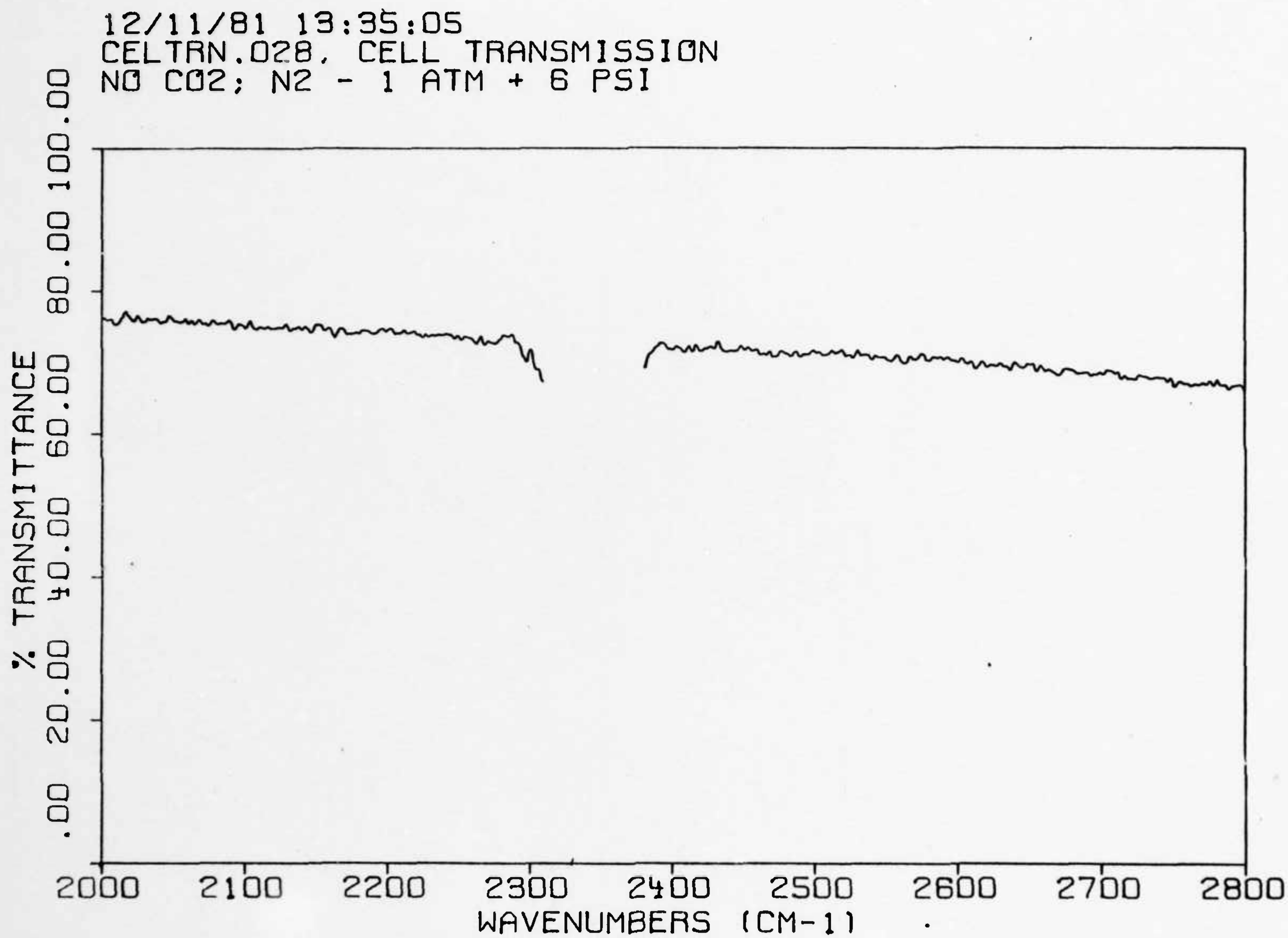


Figure A16. Measurement Number 18



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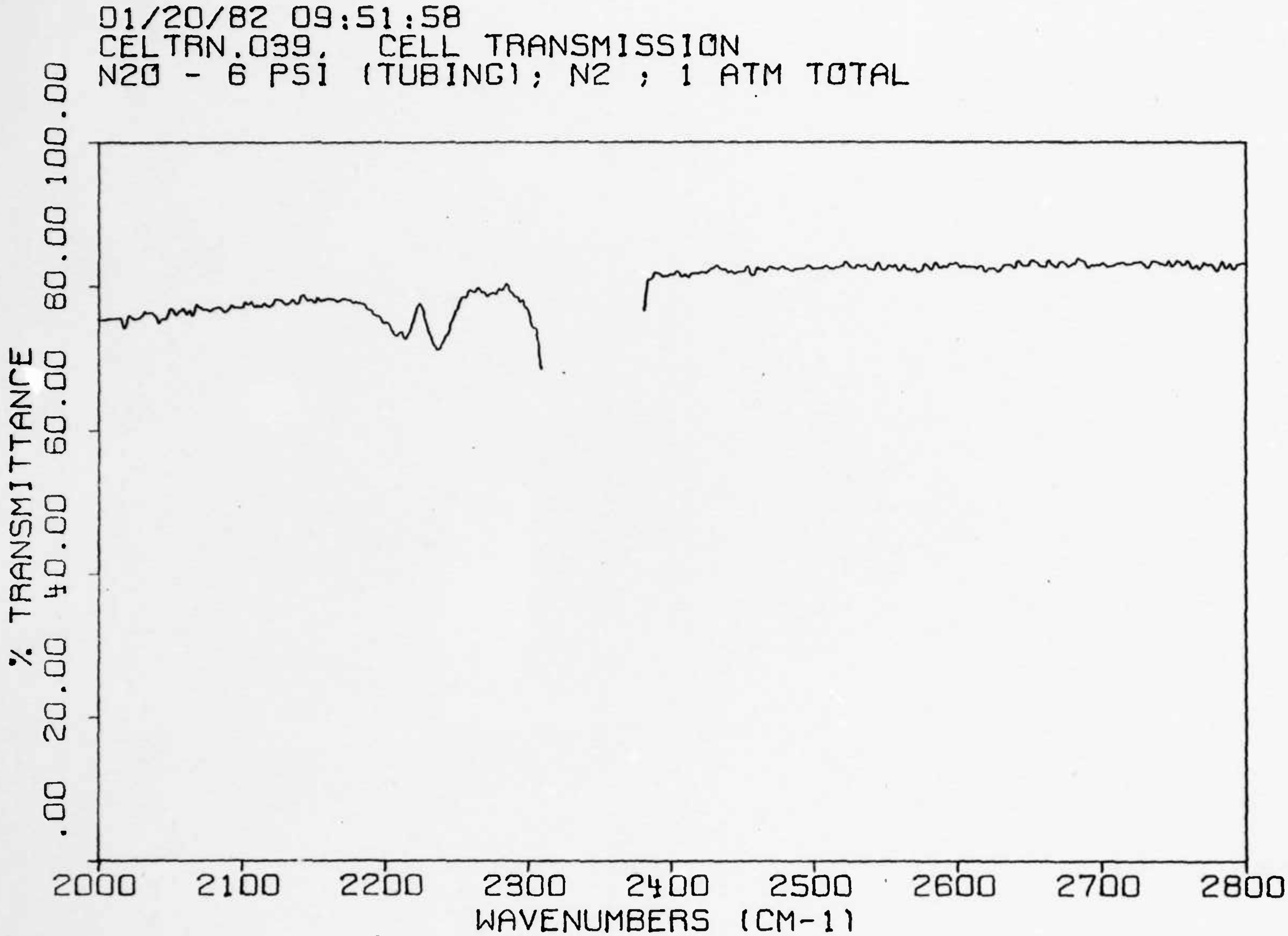

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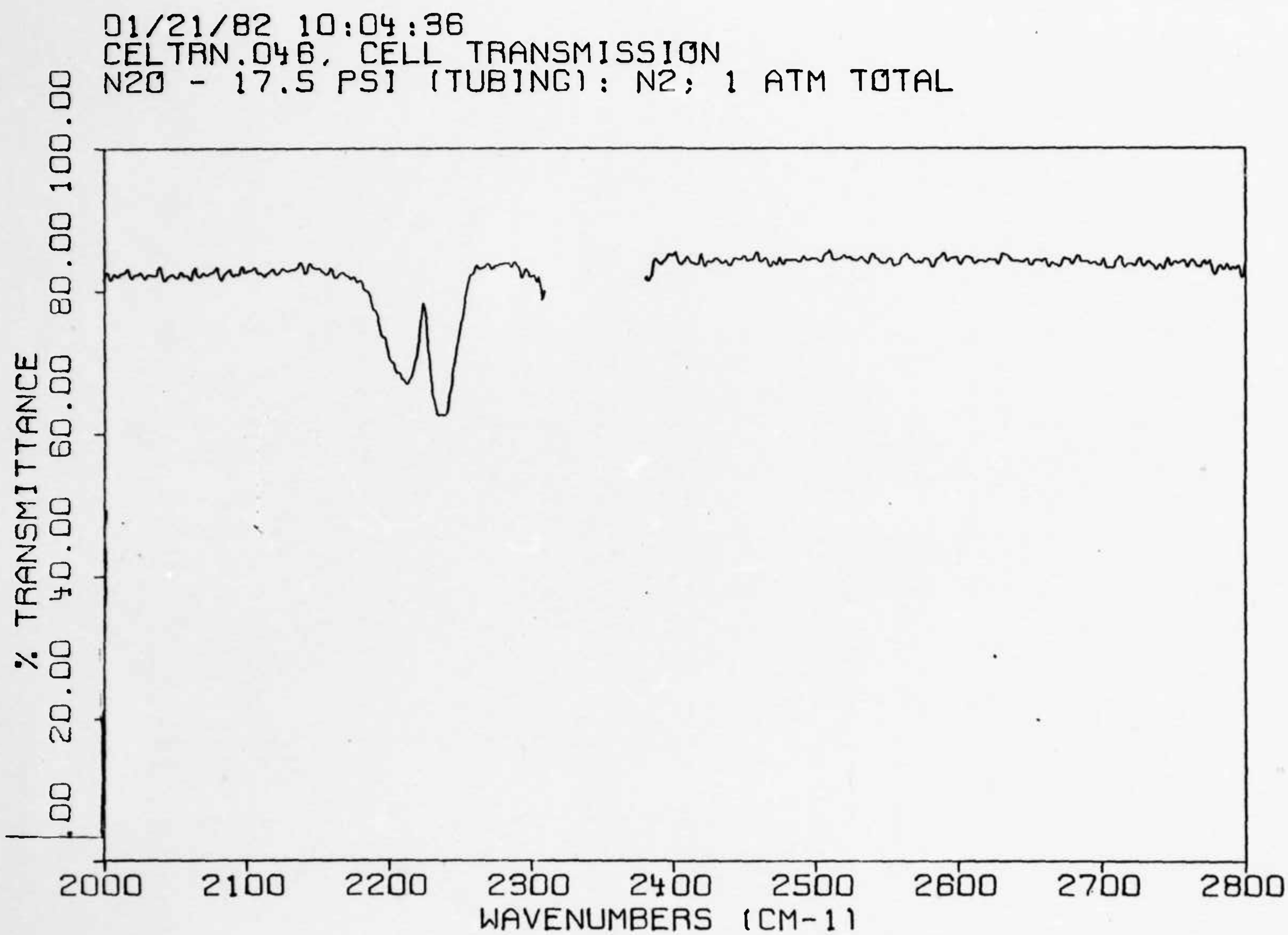

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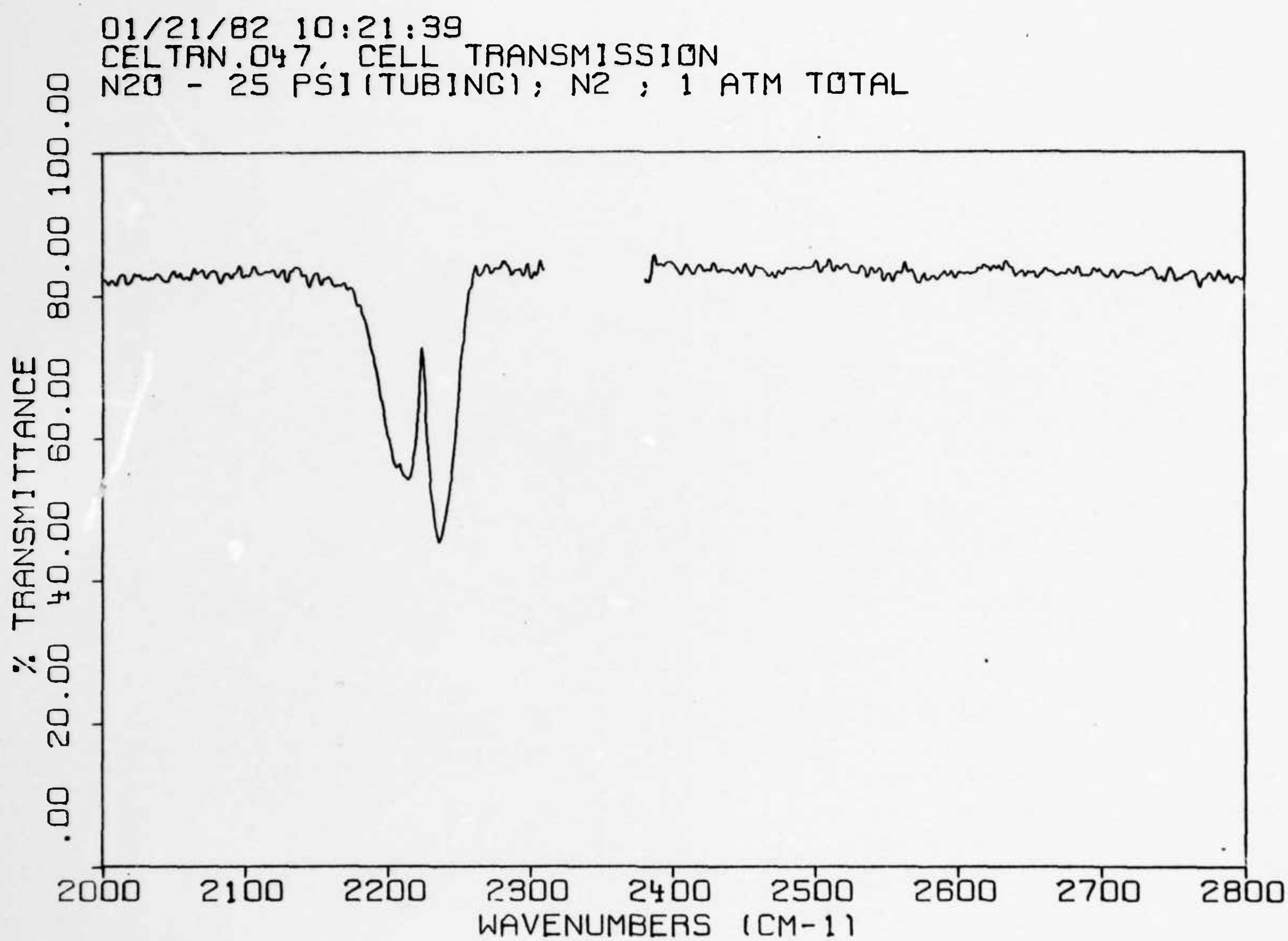

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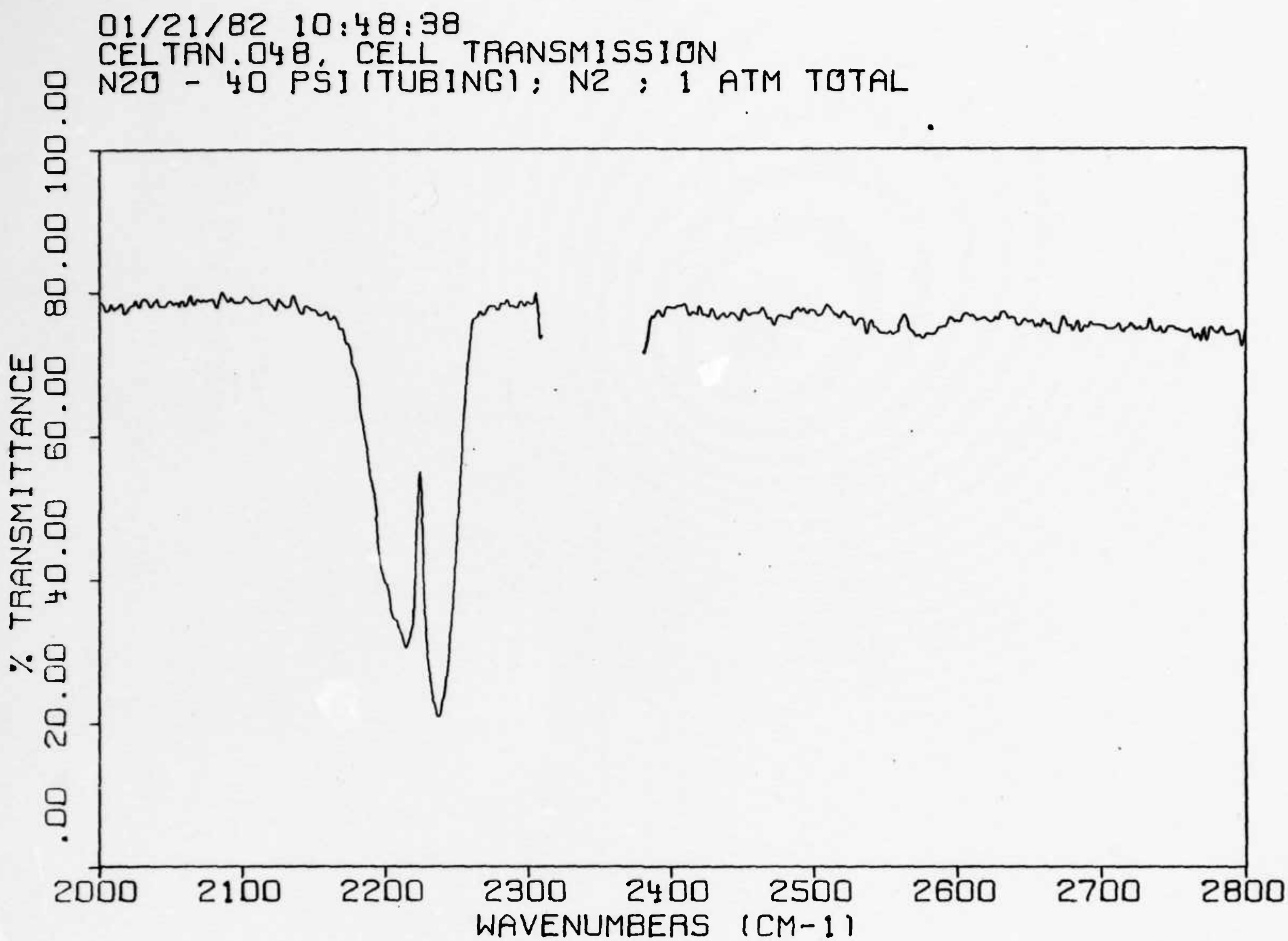

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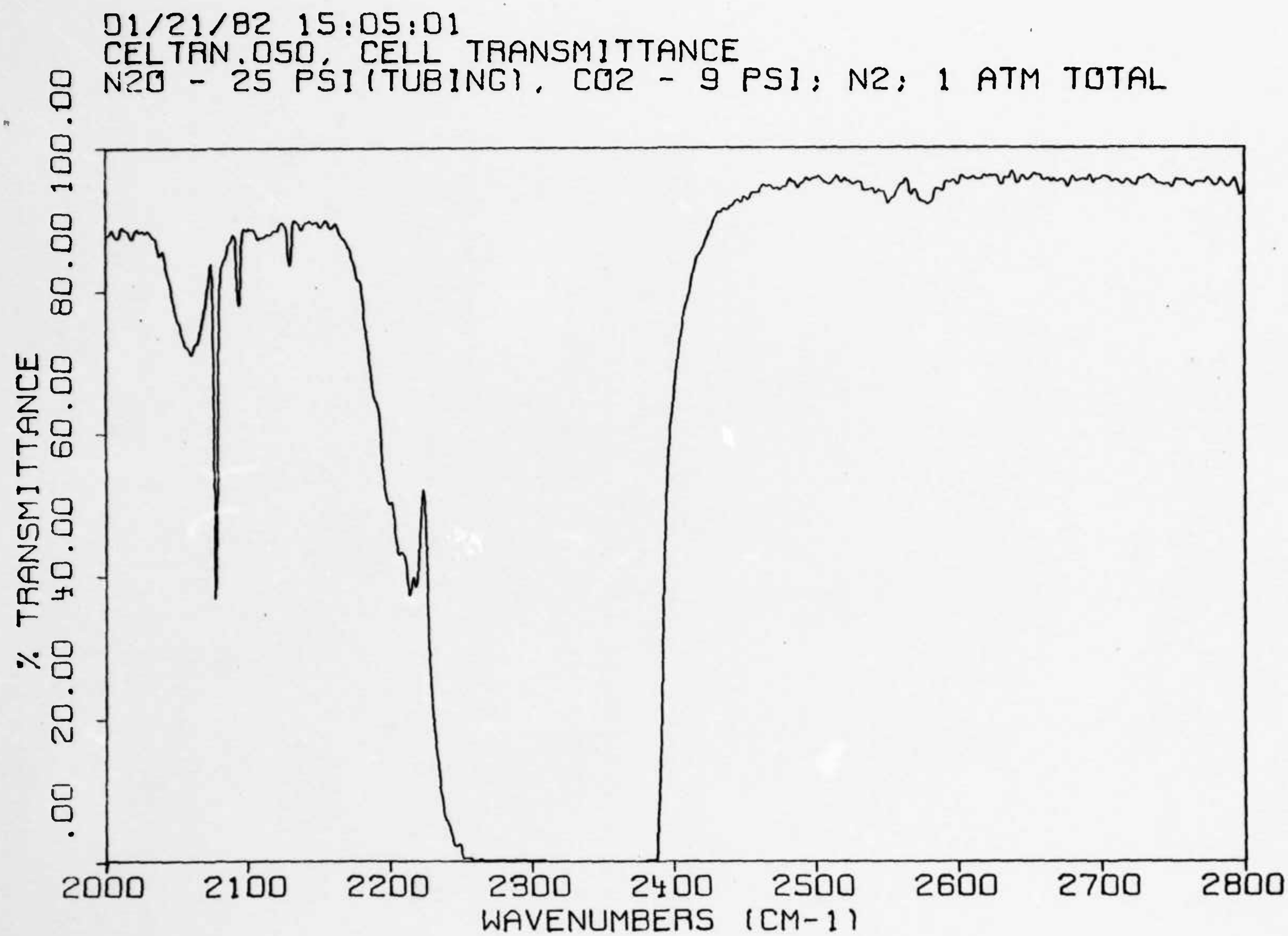

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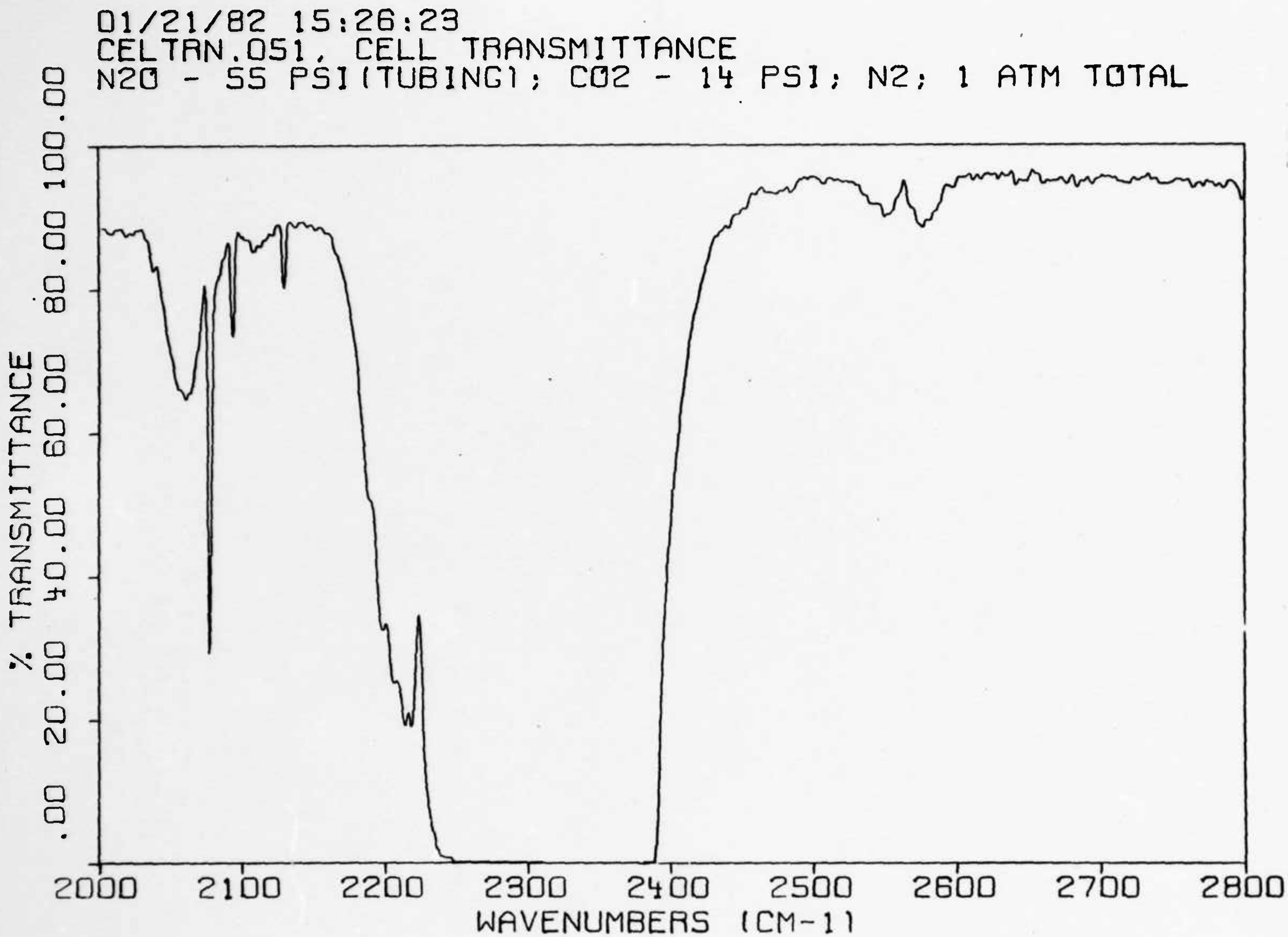

Figure A23. Measurement Number 27

VITA

Nicholas A. Pequignot was born on 24 June 1949 in Dayton, Ohio. He received the degree of Bachelor of Science in Physics from the Ohio State University in June 1971. Upon graduation, he joined the Peace Corps and served three years as a secondary school teacher in Nepal. Upon returning to the U.S. in 1975, he was employed by the Defense Electronic Supply Center in Dayton, Ohio. In 1978 he transferred to the Avionics Laboratory at Wright-Patterson AFB. In 1977 he enrolled in the School of Engineering, Air Force Institute of Technology as a part-time student.

Permanent address: 976 Kenosha Road
Kettering, Ohio 45429

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Absorption Cell	Infrared
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The measurement capability of the Avionics Laboratory IR Facility was used to evaluate an absorption cell that will be used to simulate atmospheric absorption over horizontal paths of 1-10 km in length. Band Models were used to characterize the transmittance of carbon dioxide (CO_2), nitrogen (N_2), and nitrous oxide (N_2O) in the cell. The measured transmittance was compared to the calculated values. N_2O is important in the 4 - 4.5 micron range in shaping the weak line absorption of CO_2. The absorption cell is adequate for simulating atmospheric absorption over these paths.

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